ISSN 2310-6697
otoiser—open transactions on independent scientific-engineering research

FunkTechnikPlus # Journal

Théorie—Expérimentation—Métrologie—Logiciel—Applications

ISSUE 35 — MONDAY 30 SEPTEMBER 2024 — YEAR 12 — PERIOD B'

This small European Journal is
In the Defense of Honesty in Science and Ethics in Engineering

Period B'
Previous Period 2013-2024

Publisher
otoiser—open transactions on independent scientific engineering research
ARG IAOI NFI Lab—Antennas Research Group Informal Association Of Individuals No Finance Involved Laboratory
Scheiblingkirchen, Austria

Language — We emphasize the European Origins of our Journal by using English, German and French in its title, as well as, a Hellenic vignette in the front page. However, since we recognize the dominance of US English in the technical literature, we adopted it as the Journal's language.

Focus — We consider Radio—FUNK, which still creates a vivid impression of the untouchable, and its Technology—TECHNIK, from an Advanced—PLUS point of view, Plus—PLUS Telecommunications Engineering, Electrical Engineering and Computer Science, that is, we dynamically focus at any related scientific-engineering research regarding Théorie, Expérimentation, Métrologie, Logiciel, ou Applications.

Scope — We emphasize the scope broadness by extending the title of the Journal with a Doppelkreuz-Zeichen # which we use as a placeholder for the substitution of its disciplines

Frequency — Excluding *forces majeures,* we publish 3 issues per year: on 31st of January, on 31st of May, and on 30th of September.

Editions — We increase the edition number of an issue only when is absolutely needed to reform one or more of its papers——thus to increase their version numbers——but we keep unchanged its 1st edition date shown on its front page and we number its pages sequentially from 1. We count the editions of *About* separately.

Format — We use a fixed-space font, hyphenation, justification, unfixed word spacing, and the uncommon for Journals **A5** (half A4) page size to achieve WYSIWYG printing and clear reading of 2 to 4 side-by-side pages on wide-screen displays.

Editorial Group

Submissions

We can only consider papers written in the preferable and recommended odt format of LibreOffice, or even a paper in the MS Office with MathType doc format, if it would be proved that it is fully compatible with LibreOffice indeed.

Legal Notice — It is taken for granted that the submitter–correspondent author accepts, without any reservation, the totality of our publication conditions as they are analytically detailed here, in this *About*, as well as, that he also carries, in the case of a paper by multiple authors, the independent will of each one of his co-authors to unreservedly accept all the aforementioned conditions for their paper.

Electronic Publishing

We regularly use the Free Libre Open Source Software Libre Office with the Free Liberation Mono font and the Freewares PDFCreator and PDF-Xchange Viewer. We also use some basic html code of ours and the Free Open Digital Library of Internet Archive website, where we upload the FTP#J Collection of Issues, Paper reprints, *About* documents, and Volumes, in both portrait and landscape orientations, for download or very clear online reading with the Free Open Source BookReader.

Internet Addresses

Submissions : sub@ftpj.otoiser.org
Send Updates : updates@ftpj.otoiser.org

Paper Template : https://www.template.ftpj.otoiser.org
Reference Updates : https://www.updates.ftpj.otoiser.org

Internet Publishing : https://www.ftpj.otoiser.org

The FTP#J Collection at Internet Archive Digital Library : https://archive.org/details/@funktechnikplusjournal

Please download the latest *About* edition from
https://about.ftpj.otoiser.org

Partial Discharges in Solid Insulation Cavities: Basic Concepts, Definitions and Some Thoughts for Further Research

M. G. Danikas, R. Sarathi

Democritus University of Thrace, School of Engineering, Department of Electrical and Computer Engineering, Power Systems Laboratory, 67100 Xanthi, Greece [1]

Indian Institute of Technology Madras, Department of Electrical Engineering, High Voltage Laboratory, Chennai, 600-036 India [2]

Abstract

This paper refers to some basic definitions of partial discharges (PD), a most important phenomenon taking place in insulating materials under high voltages. There is a brief description of PD modeling as well as a description of the means of detecting and registering such phenomena. This paper concentrates mainly on the PD phenomena taking place in enclosed cavities in solid insulation. Some directions of future research are discussed.

Keywords

Solid insulation, partial discharges, dielectric breakdown, dielectric strength, electrical strength, breakdown strength

Introduction

Partial discharge (PD) is the name given to the electrical discharge, which involves only a portion of the dielectric between two electrodes and which does not bridge the electrodes [1]. PD may happen in a cavity (or void) in a solid insulation (and such PD are usually referred to as internal PD), on a surface or around a sharp point subjected to a high voltage. Internal PD are extremely harmful to solid insulating materials and start appearing when a cavity is subjected to an AC stress greater than its breakdown value. They occur at each half-cycle of the applied sinusoidal voltage [2]. PD are intimately linked with the notion of PD energy, as was explained in [3], where the PD energy (w) of a single PD is given as

$$W = 0.7\, q\, V_i \quad (1)$$

where, q is the apparent charge of the PD and V_i, the discharge inception voltage.

PD develop in inclusions is a solid dielectric. Such inclusions have a lower dielectric strength than that of the surrounding material. With rising applied voltage, the voltage at which PD start occurring in an inclusion is called inception voltage. When the voltage is decreasing somehow, PD stop occurring. That voltage is called extinction voltage [4]. It must be emphasized that the quantities "inception voltage" and "extinction voltage" depend on the sensitivity of the detecting apparatus available [5 - 8]. It must also be pointed out that, reference [4] written by a most distinguished scientist, restricts the definitions of "inception voltage" and extinction voltage" to AC conditions. Inclusions in a so-lid insulation can be gas-filled cavities found in extruded plastics, lapped impregnated paper and cast re-sins, cavities filled with oil (as in layers and in butt gaps of oil impregnated paper insulation) or may consist of various foreign particles (such as textile fibers or dirt). The problem of PD and their injurious effects on so-lid insulation has been studied for many years [7, 9, 10 - 12]. This paper will concentrate on the PD in enclosed cavities in solid insulation. Some aspects of PD will be reviewed. Some of the remaining problems in conjunction to PD in cavities will be discussed.

PD modeling

The most popular and widely used model for the description of the behavior of PD in enclosed cavities is the well known a-b-c model or capacitance model [13, 14]. The model represents the enclosed cavity as a capacitor (C_c), with another capacitor the adjacent insulation (C_b) and yet another capacitor the rest of the healthy insulation (C_a). In case of an applied AC voltage V_a to the insulation sample, another voltage V_c appears in the cavity, with these voltages related with the following equation

$$V_c = V_a\,[C_b / (C_b + C_c)] \quad (2)$$

According to appropriate analysis [3], it follows that the apparent charge (q) of a discharge in a cavity can be expressed as

$$q = C_b \, \Delta V_c \quad (3)$$

with ΔV_c the voltage drop in the cavity during the PD.

Another model – based on the electromagnetic theory – is the model proposed in [15], where the charge (q) induced on the measuring electrode by the PD in a cavity of geometric factor (k) and having a volume (Ω), with the inception electric field for streamer inception (E_i) and a limiting electric field for ionization (E_l), the relative permittivity of the surrounding insulation (ε_r) with (ε_0) the permittivity of the free space, and $\nabla\lambda_0$ the function giving the ratio of the electric field at the position of a cavity (in the absence of the cavity) to the voltage between the electrodes, is given in the following equation

$$q = k \, \Omega \, \varepsilon_r \, \varepsilon_0 \, (E_i - E_l) \, \nabla \lambda_0 \quad (4)$$

This model was based on the streamer criterion and it was proved adequate for initial experimental conditions. The criticism which was leveled by Pedersen and colleagues against the a-b-c model was that an enclosed cavity cannot be represented as a capacitance since a capacitance by definition requires a metallic surface facing a metallic surface. In a paper [16], some criticism was leveled against Pedersen’s model, namely that whereas publication [15] takes into account the occurrence of sustained discharges, it does not take into account the eventuality of non-sustained discharges. Non-sustained discharges may well not only lead to a redistribution of charges inside a cavity, but they may also have an effect on the lifetime of the insulation. Later on, there was additional criticism of Pedersen’s model in a number of publications [17 – 19].

Another model – which preceded Pedersen’s model – was proposed in [20]. Although the models of [15] and [20] present some similarities, they differ in that the latter is based on Townsend’s criterion. The equation expressing the apparent charge q of a PD taking place in a cavity is given in Eq. (5)

$$q = \varepsilon_r \, \varepsilon_0 \, E_z \, \gamma \, V / l_a \quad (5)$$

where, ε_r, ε_0 as in Eq. (4) above, E_z the electric field given from Paschen’s curve, γ a parameter related to the electrode arrangement, V the cavity volume and l_a a geometrical factor depending on the cavity dimensions, i.e.

on the ration a/b if the cavity is ellipsoidal. The model proposed in [20] seems to be more appropriate for rather aging conditions whereas the model of reference [15] seems to be more suitable for initial experimental conditions.

More recently, a detailed account on PD modeling was reported in [21], where the authors analyzed – apart from the capacitance model and Pedersen’s model - the pros- and cons - of other models, such as Niemeyer’s model, the plasma model and the Finite Element Method (FEM) model. It is a general truth that modeling cannot fully describe all the PD workings occurring in a cavity. Therefore, the above mentioned models have their own advantages and limitations. Niemeyer’s model, for example, correctly proposes cavity surface emission and volume ionization but it assumes that the cavity internal field remains constant and the discharge process takes place in the entire cavity. The plasma model gives details of the physics of the discharge but it cannot analyze multiple PD activities (e.g., in case there are multiple cavities in an insulation). The FEM model may well give accurate distributions of the electric fields but in case of complex physical activities may need extensive computing facilities [21].

PD in cavities

Mason [22] testing with plane discs from clean polyethylene with small cylindrical cavities and using uniform electrode arrangement, calculated that about 10^{-15} cm^3 of polyethylene is eroded by each PD having a 10 pC magnitude. The same researcher reported that deterioration of the dielectric increased with raising the applied voltage above the PD inception level. Among the main factors affecting the rate of deterioration of an insulating material are the ratio of the applied voltage to the PD inception voltage, the magnitude and energy of the PD, the waveform and frequency of the applied voltage, the resistance of the material both to PD erosion and to chemical attack by byproducts generated by the discharge and finally the electrical and chemical characteristics of the surrounding medium [23]. The energy of the discharges affects the local temperature rise at the point of impact of the PD and subsequently the value of the attained intrinsic strength. (it must be noted that the notion of "intrinsic strength", although still employed when referred to very localized phenomena, is not generally used [24]).

Earlier work [25], investigating the behavior of discharges in air gaps facing solid insulation, indicated that the increase of PD magnitude with increasing voltage was due to a continuous recombination and neutralization of deposited surface charges which reduce the shielding effect. Rogers [26] remarked that cavities adjacent to electrodes cause more damage than cavities inside the main body of the solid insulation, something that was also noted before [22]. Moreover, PD in cavities with a large diameter/depth ratio cannot extinguish as in cavities with a small diameter/depth ratio. The former type of cavities is likely to have the more injurious effect on the insulation. Such observations were also made by Nosseir and co-workers [27], whereas decades later, the observations by Rogers were also confirmed in [28].

Another researcher [29], many decades ago, tested two types of insulating specimens, namely one with artificial cavities and another with natural cavities and he found that the inception voltage of natural cavities was two to four times the calculated inception voltage, assuming the field was uniform in the cavity. Echoing such work, Kreuger [30] observed that PD magnitude increases with cavity area, with the number of PD per unit time increasing proportionally with frequency.

Quite early, particular attention was paid to the interconnection between insulation damage and chemical changes. Thus, it was reported in [31] that on non-uniform electrode system and polyethylene samples, the main chemical changes occurring – by the activity of PD – are crosslinking, increase in unsaturation and hydrogen evolution. The rate of chemical change depends on the total PD energy and the concentration of the end products. The total volume of hydrogen evolution V (in ml) in a system at a time t (in sec) was empirically given in Eq. (6)

$$V = \sqrt{2}\,kt \qquad (6)$$

with k the hydrogen evolution coefficient, which is directly proportional to the total PD energy per cycle. In the same publication it was pointed out that weakly conducting films play a significant role in retarding the ultimate failure of the solid insulation, agreeing in this respect with Kreuger [30, 32]. Somehow coupled with the previously mentioned work is a paper published in 1965, where it was shown that the PD rate rises almost linearly with the applied voltage irrespective of the gap setting and the vapor pressure in a spark gap [33].

The question of PD and their relation to energy as well as to insulation damage is one of the most crucial ones. Megahed and co-workers [34] thought preferable to measure continuously both PD magnitudes and repetition rates in order to correlate PD damage with PD activity rather than measure either the maximum PD magnitude or the total PD energy. Later [35], Megahed confirmed the above conclusions studying the PD repetition rates in cavities in epoxy resin, polyethylene and mica under AC conditions. At about the same period, other researchers working on internal PD behavior in polyethylene with artificial cavities, reported that PD generally decrease in magnitude and repetition rate with time and that absorbed water can greatly influence the pattern of discharges [36]. The decrease of repetition rate of PD with time occurs because of a voltage decrease on the side wall due to the decline of the side wall resistance in the cylindrical cavity. The apparent charge of maximum PD (q_a) in a cylindrical cavity is given by Eq. (7)

$$q_a = (\varepsilon_0 \, \varepsilon \, V_{GO} \, s) \, / \, (D - d) \qquad (7)$$

with ε_0 the dielectric constant of vacuum, ε the dielectric constant of the solid material, D the thickness of the specimen, d the cavity depth, s the area of the cavity and V_{GO} the inception voltage of the cavity. The diminution of q_a with time is due to the narrowing of the discharge area by the development of low resistance to inner top and bottom surfaces. Results published in [37] at about the same period showed that the impulse inception stress increases with decreasing cavity diameter at constant cavity depth as well as with decreasing depth at constant cavity diameter. Such data on the effect of cavity dimensions on the PD activity and on inception voltage were confirmed in more recent research [38 – 40].

Okamoto and co-workers [41] pointed out that the nature of internal PD is greatly affected by the assembly of the electrode system and the adhesion of films. This means that the preparation procedure plays a pivotal role on the experimental results one can get. Furthermore, they reported that internal discharges become unstable as time goes on and this in turn may result in very long lifetimes. Such conclusions were confirmed later in [42, 43].

Selvakumar and Nema [44] found that the PD inception voltage depends on both the pressure within the cavity and on the cavity diameter, with the PD inception voltage decreasing at low pressures. PD inception voltage also decreases approaching a minimal value as the diameter becomes larger. The extinction voltage, on the other hand, depends on the conditions of charges trapped on the surface of the insulation. They reported that, for consistent measurements of quantities such as inception voltage, of stress across the cavity and of extinction voltage, long periods of stressing are recommended and not overvoltages since the latter may damage the insulation. The effect of cavity pressure on PD behavior was confirmed the same year by other researchers [45]. Important work done in [27], indicated that a hysteresis effect exists between inception and extinction voltage, i.e. for the same applied voltage V, the PD magnitude recorded was less when the voltage was being decreased than when the applied voltage was being increased. The hysteresis effect was more pronounced for deeper cavities. The authors attributed this to the slower rate of discharge leakage in case of deeper cavities. The hysteresis effect – as noted in [27] – was studied and used many years later as an effective diagnostic tool for electrical machine insulation ageing and degradation [46 – 48].

A direct relationship between PD intensity and the rate at which deterioration takes place in an internal cavity was observed by Reynders [49], who worked with low density polyethylene (LDPE). His observations were confirmed in another paper published a few years later [50]. Reynders noted a phenomenon observed also by others before, namely that PD initially of large magnitude decrease with time. Such a behavior may be attributed to the diminishing of the cavity area associated with each PD with time and this can happen if the PD occur between sites where degradation products accumulate. As the degradation products spread over the cavity surface, smaller areas between them are available to PD [51]. Regarding the degradation of LDPE, two degradative processes were observed:

(a) crosslinking of polyethylene, which may be due to ultraviolet radiation and electrons and this is evident by hydrogen evolution, and

(b) erosion of polyethylene, which may be due to ion bombardment and the evolution of organic gases, such as carbon monoxide, methane and carbon dioxide [52].

With respect to process (a), publication [52] did not differ from the explanation of [31].

Researching the notion of inception voltage, Golinski and co-workers [53] studied PD activity in cylindrical cavities enclosed in epoxy resin specimens with various electrode geometries. They observed that the effect of polarity is distinct only in the region where $V = V_{vi}$ (V being the applied voltage and V_{vi} the inception voltage for the cavity). At V = (3 or 4) V_{vi} the effect of polarity almost disappeared. They speculated that at higher voltage the important secondary phenomena (photoionization, dissociation of the negative ions formed by the preceding PD) in gas breakdown originate from the gas and not from the metal electrodes.

Garcia and Fallou [54] proposed discharge energy as a reliable and useful tool in evaluating the relationship between loss of weight and dissipated power since the apparent charge reflects just the voltage pulse induced at the terminals of the test object providing thus little information concerning the deteriorating effect of the PD. The energy delivered to the test object is expressed according to these authors as

$$E_T = \Sigma U_i Q_i \qquad (8)$$

where, E_T is the energy supplied by the source over a period T during which N discharges have taken place, Q_i and U_i being respectively apparent charge of the PD and U_i the instantaneous value of applied voltage when the PD takes place. The conclusions of [54] were not different from those reported in [55, 56]. The notion of discharge energy was adopted by a variety of researchers later, especially with the advent of Pulse Height Analyzers (PHA) and Phase Resolved Partial Discharges Analysis (PRPDA) [57 - 65]. The latter two techniques also greatly contributed in observing various PD patterns as was reported and analyzed in [21, 66] as well as in analyzing in detail the cavity physics and chemistry when this is under PD activity. Furthermore, relatively recent studied successfully exploited PHA and PRPDA in order to relate energy patterns of delaminations, slot and cavities in high voltage rotating machines with tanδ measurements [67].

Ideas as to the importance of PD energy in relation to insulation damage were expressed quite early. The complexities of PD energy vs. PD magnitude were very early noted by Mole [68], who suggested that the energy dissipation of an individual discharge in a cavity appeared to be more important than the PD magnitude. In the same paper it was pointed out the significance of the cumulative energy dissipation in a cavity (which was determined by the individual energy dissipation together with the PD repetition frequency in a particular cavity). Building on earlier ideas and concepts, Bartnikas [2] expressed the energy dissipated in each discharge as

$$\Delta W = C_V (\Delta V)^2 / 2 \qquad (9)$$

where, C_V the cavity capacitance and ΔV the voltage drop in the cavity during a discharge. The same author correctly pointed out the great significance of the PD energy because of its direct relationship to the degradation of an insulation subjected to PD. Starr [69] reported that the spatial concentration of the PD energy is very important, since in some cases, discharges alter the material on which they impinge rendering it partially conductive and consequently removing the electrical stress from the area where the discharges firstly occurred. This may well cause the discharge mechanism process to cease or start somewhere else. A consequence of the above is that a discharge energy / material damage relationship may be different from what is expected.

The question as to how we can relate insulation damage with PD parameters is one of the crucial problems. Insulation damage, depending on the material and the experimental and/or the service conditions, may manifest itself in various forms, e.g. discolored areas, chemical alterations, solid by-products, liquid by-products, gaseous by-products etc. It was reported that even very small PD may cause some insulation damage, and consequently affect the lifetime of an insulation [70]. This statement is at variance with earlier findings of [30], where it was reported that "...very small discharges may not influence the lifetime of the insulant". In [70] as well as in more recent publications [71 - 75], it was indicated that even very small PD may have a cumulative effect and be harmful since in the mid- and long- term may produce more carbonization, disruption of the polymer molecules and release of gaseous by-products.

The failure of earlier researchers [76] to obtain a more explicit quantitative relationship between insulation damage and PD parameters was remedied in more recent years with the advent of powerful tools of PD analysis, such as the PHA and the PRPDA mentioned above as well as the Pulse-Sequence Analysis (PSA) [77 - 80]. Needless to say that such techniques also help with the identification of the types of the defects in an insulation and also with the clarification of the kind of PD mechanisms involved [81 - 84].

Some further thoughts on partial discharges

In this paper, an effort was made to present a blend of older and more recent research regarding partial discharges in enclosed cavities. It is evident that scientific research has a continuity and it is always very interesting to see how recent techniques may tackle older problems. Although there was not a dramatic change in basic PD definitions - albeit sometimes of efforts in introducing neologisms [85, 86] -, the development of PD analyzers and related detecting techniques emphasized the need of defining in greater detail what is inception voltage and what is extinction voltage. With the passing of the years, the refinement of detecting apparatus and the advent of the fast digitizers, more attention – and rightly so - was paid to the fast measurements of PD [87, 88]. The latter may supply useful information as to the PD mechanism inside a cavity, whereas the techniques PHA and PRPDA, mentioned above [57 - 65], are an excellent tool for monitoring the PD cavity development and consequently the insulation behavior in the mid- and the long- term. Some criticism against the PHA and PRPDA techniques was leveled recently, by pointing out that the former two methods are sometimes susceptible to losing useful information when multiple PD sources are in action [89]. Possible future research may enlighten further the pros- and cons- of the various diagnostic techniques.

Regarding the modeling of PD in a cavity, discussions still go one regarding the preponderance of Pedersen’s model [15] w.r.t. the more classical capacitance model [13, 14]. The issue is not yet settled, as some recent publications indicate [17 - 19, 90, 91].

Conclusion

In the context of the present paper, some aspects of partial discharges in enclosed cavities have been partially reviewed. Important issues, such as inception and extinction voltages, PD energy and its relation to insulation damage, have been discussed. The interconnection between PD energy and what can be taken as "insulation damage" is still one of the vital subjects for further research.

References

[1] Timpe N. B., "Partial discharge measurements in distributed parameter systems: Cables", Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 134 - 175

[2] Bartnikas R., "Corona discharge processes in voids", Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 22 – 67

[3] Gallagher T. J., Pearmain A. J., "High Voltage – Measurement, Testing and Design", Eds. John Wiley & Sons, New York, USA, 1983, pp. 166 – 168

[4] Kelen A., "Studies on partial discharges on solid dielectrics: A contribution to the discharge resistance testing of insulating materials", Acta Polytechnica Scandinavica, No. EI 16, Monograph, 1967, total number of pages 138

[5] Tanaka T., Greenwood A., "Advanced power cable technology: Volume I – Basic concepts and testing", Eds. CRC Press, Boca Raton, Florida, USA, 1983, p. 87

[6] Mason J. H., "Dielectric breakdown of solid insulation", Progress in Dielectrics, Vol. 1, 1959, pp. 1 – 58

[7] Mason J. H., "Discharges", IEEE Transactions on Electrical Insulation, Vol. 13, No. 4, 1978, pp. 211 – 238

[8] Danikas M. G., Sarathi R., "Very small partial discharges and charging phenomena below inception voltage: An effort for a review and a proposal for a unified theory", FunkTechnikPlus # Journal, Issue 33, Year 11, 2024, pp. 7 - 27 "www.ftpj.otoiser.org/issues/html/ftpj-issue-33-lo7532-export-ia1.htm" (33-1)

[9] Morshuis P., "Assessment of dielectric degrada-tion by ultrawide-band PD detection", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, 1995, pp. 744 – 760

[10] Kelen A., Danikas M. G., "Evidence and presumption in PD diagnostics", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, 1995, pp. 780 – 795

[11] Koenig D., "Das Phaenomen der elektrischen Teilentladung", in the book "Teilentladungen in Betriebsmitteln der Energietechnik", Eds. VDE-Verlag, Berlin und Offenbach, Germany, 1993, pp. 15 – 39

[12] Moeller K., Meurer D., "Auswirkungen von Teilentladungen auf elektrische Isolierstoffe", in the book "Teilentladungen in Betriebsmitteln der Energietechnik", Eds. VDE-Verlag, Berlin und Offenbach, Germany, 1993, pp. 85–104

[13] Gemant A., "Die Verlustkurve lufthaeltiger Isolierstoffe", Zeitschrift der Technischen Physik, Vol. 13, 1932, pp. 184 – 189

[14] Gemant A., Philippoff W. V., "Die Funkenstrecke mit Vorkondensator", Zeitschrift der Technischen Physik, Vol. 13, 1932, pp. 425 – 430

[15] Crichton G. C., Karlsson P. W., Pedersen A., "Partial discharges in ellipsoidal and spheroidal voids", IEEE Transactions on Electrical Insulation, Vol. 24, No. 2, 1989, pp. 335 – 342

[16] Danikas M. G., Vardakis G. E., "The case of Pedersen's theory to model partial Discharges in cavities enclosed in solid insulation: A criticism of some of its aspects from an electrical engineers' and from a physicists' point of view", Journal of Electrical Engineering, Vol. 52, No. 5-6, 2001, pp. 166 – 170

[17] Achillides Z., Georghiou G. E., Kyriakides E., "Partial discharges and associated transients: The induced charge concept versus capacitive modeling", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 6, 2008, pp. 1507 – 1516

[18] Achillides Z, Danikas M. G., Kyriakides E., "Partial discharge modeling and induced charge concept: Comments and criticism of Pedersen's model and associated measured transients", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 24, No. 2, 2017, pp. 1118 – 1122

[19] Achillides Z., Kyriakides E., Danikas M. G., "Partial discharge modeling: An advanced capacitive model of void", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 26, No. 6, 2019, pp. 1805 – 1813

[20] Repp H., Nissen K. W., Roehl P., "Partial discharges in voids: Inception Conditions and detection limits", Siemens Forschung und Entwicklung Bericht, Vol. 12, 1983, pp. 101 – 106

[21] Afrouzi H.-N., Hassan A., Ye Chee D. T., Mehranzamir K., Malek Z. A., Mashak S. V., Ahmed J., "In-depth explorations of partial discharge modelling Methods within insulations", Cleaner Engineering and Technology, Vol. 6, 2022, total number of pages 13
"https://doi.org/10.1016/j.clet.2021.100390"

[22] Mason J. H., "The deterioration and breakdown of dielectrics resulting from internal discharges", Proceedings of IEE, Vol. 98, Part I, 1951, pp. 44 – 59

[23] Mason J. H., "Breakdown of insulation by discharges", Proceedings of the IEE, Vol. 100, Part IIA, 1953, pp. 149 – 158

[24] Cooper R., "Breakdown in solids", in the book "Electrical Insulation" edited by A. Bradwell, eds. Peter Peregrinus, London, UK, 1983, pp. 33 – 51

[25] Frielander E., Reed J. R., "Electrical discharges in air-gaps facing solid insulation in high-voltage equipment", Proceedings of the IEE, Vol. 100, Part IIA, 1953, pp. 121 – 131

[26] Rogers E. C., "The self-extinction of gaseous discharges in cavities in dielectrics", Proceedings of the IEE, Vol. 105A, 1958, pp. 621 – 630

[27] Nosseir A., Salama M. M. A., Soliman A., Rizk R., "Discharge detection and measurement in voids in solid dielectrics", Conference Record of 1984 IEEE International Symposium on Electrical Insulation, Montreal, Canada, June 11-13, 1984, pp. 336 – 338

[28] Hossam-Eldin A. A., Dessouky S. S., El-Mekkawy S. M., "Internal discharge in solid dielectric materials", Journal of Electrical Engineering, Vol. 9, No. 4, 2009, total number of pages 5
"www.jee.ro"

[29] Reynolds S. I., "On the behavior of natural and artificial voids in insulation under internal discharges",

AIEE Transactions on Power, Apparatus and Systems, Vol. PAS-77, Part III, 1959, pp. 1604 – 1608

[30] Kreuger F. H., "Discharge detection in high voltage equipment", Eds. Heywood London, UK, 1964, pp. 105 - 125

[31] Meats R. J., Stannett A. W., "Degradation of insulation materials by electrical discharges", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-83, 1964, pp. 49 – 54

[32] Kreuger F. H., "Industrial High Voltage: Fields, Dielectrics, Constructions", Eds. Delft University Press, Delft, The Netherlands, 1991, pp. 123 – 131

[33] Bartnikas R., d'Ombrain G. L., "A study of corona discharge rate and energy loss in spark gaps", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-84, No. 9, 1965, pp. 770 – 778

[34] Megahed I. Y., Mansfield B. C., Wootton R. E., "Detection and measurement of discharges in cavities in solid dielectrics", Proceedings of the IEE, Vol. 114, No. 11, 1967, pp. 1822 – 1824

[35] Megahed I. Y., "The discharge-repetition rate in cavities in epoxy resin, polyethylene, and mica under alternating voltage conditions", IEEE Transactions on Electrical Insulation, Vol. EI-10, No. 2, 1975, pp. 69 – 74

[36] Tanaka T., Ikeda Y., "Internal discharges in polyethylene with an artificial cavity", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-90, No. 4-6, 1971, pp. 2692 – 2702

[37] Densley R. J., Salvage B., "Partial discharges in gaseous cavities in solid dielectrics under impulse voltage conditions", IEEE Transactions on Electrical Insulation, Vol. EI-6, No. 2, 1971, pp. 54 – 62

[38] Ramachandra B., Nema R. S., "Characterization of partial discharge pulses in artificial voids in polyethylene films used in capacitors", Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, Montreal, Quebec, Canada, June 16-19, 1996, pp. 517 – 520

[39] Kolcunova I., Sipos M., "Measurement of partial discharge in disc-shaped voids", Proceedings of the 8th International Scientific Symposium ELEKTROENERGETIKA 2015, Stara Lesna, Slovak Republic, August 16-18, 2015, pp. 334 – 337

[40] Srinivasa D. M., Harish B. N., Harisha K. S., "Analysis study on partial discharge magnitudes to the parallel and perpendicular axis of a cylindrical cavity", International Journal of Engineering Trends and technology (IJETT), Vol. 45, No. 7, 2017, pp. 334 – 337

[41] Okamoto H., Kanazashi M., Tanaka T., "Deterioration of insulating materials by internal discharge", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-96, No. 1, 1977, pp. 166 – 177

[42] Kim Y. J., Nelson J. K., "Assessment of deterioration in epoxy/mica insulation", IEEE Transactions on Electrical Insulation, Vol. 27, No. 5, 1992, pp. 1026 – 1039

[43] Gjaerde A.-C., Sletbak J., "Influence of partial discharges on void gas pressure", Proceedings of International Conference on Partial Discharge, Canterbury, UK, September 28-30, 1993, pp.119 – 120

[44] Selvakumar S., Nema R. S., "Low pressure discharges in narrow cylindrical voids", Proceedings of the 3rd International Conference on Dielectrics, Materials, Measurements and Applications, Birmingham, UK, September 10-13, 1979, pp. 113 – 115

[45] Stenerhag B., Danemar A., "Partial discharge characteristics of some liquid impregnated systems", Proceedings of the 3rd International Conference on Dielectrics, Materials, Measurements and Applications, Birmingham, UK, September 10-13, 1979, pp. 26 – 29

[46] Danikas M. G., "A novel diagnostic technique to study the ageing of rotating machine insulation: The "Hysteresis Phenomenon" based on partial discharge measurements", Acta Polytechnica (Journal of Advanced Engineering Design), Vol. 40, No. 5-6, 2000, pp. 91 – 97

[47] Danikas M. G., Karlis A. D., "Diagnostic techniques in rotating machine insulation: A diagnostic technique for model stator bars based on the maximum partial discharge magnitude", Electric Power Components and Systems, Vol. 34, No. 8, 2006, pp. 905 – 916

[48] Danikas M. G., Karlis A. D., "The hysteresis curve of the maximum partial discharge magnitude as a diagnostic technique for model stator bars", Proceedings of the 2006 International Conference on Electrical Machine Systems (ICEMS), Nagasaki, Japan, November 20-23, 2006, Session DS1F4, Paper no. 05

[49] Reynders J. P., "Electrical detection of degradation caused by partial discharges in polythene", Proceedings of International Conference on Dielectric Materials, Measurements and Applications, Cambridge, UK, July 21-25, 1975, pp. 19 – 22

[50] Reynders J. P., "Measurement of the effects of partial discharge activity on low density polyethylene", Proceedings of the 3rd International Conference on Dielectric Materials, Measurements and Applications, September 10-13, 1979, pp. 97 – 100

[51] Opoku R. R., Robles E. G., Mason J. H., "Degradation and breakdown polypropylene film by internal discharges", Proceedings of the IEE International Conference on Dielectric Materials, Measurements and Applications, Cambridge, UK, July 21-25, 1975, pp. 323 – 326

[52] Wolter K. D., Tanaka J., Johnson J. F., "A study of gaseous degradation products of corona-exposed polyethylene", IEEE Transactions on Electrical Insulation, Vol. 17, No. 3, 1982, pp. 248 – 252

[53] Golinski J., Calderwood J. H., Zoledziowski S., Sierota A., "Partial discharges in a cylindrical void with a metal rod electrode", IEEE Transactions on Electrical Insulation, Vol. 17, No. 6, 1982, pp. 560 – 569

[54] Garcia G., Fallou B., "Equipment for the energy measurement of partial discharges", Proceedings of the 1st International Conference on Conduction and Breakdown in Solid Dielectrics, July 4-8, 1983, Toulouse, France, pp. 275 – 281

[55] Viale F., Poitevin J., Fallou B., Morel J. F., Buccianti R., Yakov S., Cesari S., Serena E., "Study of a correlation between energy of partial discharges and degradation of paper-oil insulation", CIGRE, Report 15-12, 1982, pp. 1 – 9

[56] Lehmann K., "Teilentladungs- Monitoring an Grossgeneratoren", Ph.D. Thesis, ETH Zuerinch, Hochspannungstechnik Laboratorium, 1994

[57] Koyanagi E., "Partial discharge measurement with pulse analysis", Proceedings of 1980 IEEE International Symposium on Electrical Insulation, Boston 80 CH1496-9-EI, 1980, pp. 171 – 174

[58] Hikita M., Yamada K., Nakamura A., Mitsutani T., Oohasi A., Ieda M., "Measurements of partial discharges by

computer and analysis of partial discharge distribution by the Monte Carlo method", IEEE Transactions on Electrical Insulation, Vol. 25, No.3, 1990, pp. 453 – 468

[59] Gulski E., Kreuger F. H., vComputer-aided recognition of discharges sources", IEEE Transactions on Electrical Insulation, Vol. 27, No. 1, 1992, pp. 82 - 92

[60] Danikas M. G., "Study of samples of a composite insulating system under electrical and thermal stresses", IEEE Electrical Insulation Magazine, Vol. 6, No. 1, 1990, pp. 18 – 23

[61] Krivda A., Gulski E., Satish L., Zaengl W. S., "The use of fractal features for recognition of 3-D discharge patterns", IEEE Transactions on Dielectrics and electrical Insulation, Vol. 2, No. 5, 1995, pp. 889 – 892

[62] Fruth B., Fuhr J., "Partial discharge pattern recognition - A tool for diagnosis and monitoring of Aging", CIGRE Main Session 1990, Paris, Paper 15/33-12

[63] Das S., Purkait P., "φ-q-n pattern analysis for understanding partial discharge Phenomena in narrow voids", Proceedings of the 2008 IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, July 20-24, 2008, total number of pages 7

[64] Vogelsang R., Fruth B., Froehlich K., "Detection of electrical tree propagation in generator bar insulations by partial discharge measurements", Proceedings of the 7th International Conference on properties and Applications of Dielectric Materials, June 1-5, 2003, Nagoya, Japan, pp. 281 – 285

[65] Kai R., Yamanoue T., Tanaka H., Kawano H., Kozako M., Hikita M., "A study of PRPD statistics to improve the performance of PD detection and defect type identification", Proceedings of the 9th International Conference on Condition, Monitoring and Diagnosis 2022 (CMD 2022), November 13-18, 2022, Paper P3-24, total number of pages 6

[66] Rodriguez-Serna J. M., Albarracin-Sanchez R., Dong M., Ren M., "Computer simulation of partial discharges in voids inside epoxy resins using three-capacitance and analytical models", Polymers, Vol. 12, No. 77, total number of pages 26
"http://www.mdpi.com/journal/polymers"

"http://dx.doi.org/10.3390/polym12010077"

[67] Deshpande A. S., Mangalvedekar H. A., Cheeran A. N., "Partial discharge analysis using energy patterns", Electrical Power and Energy Systems, Vol. 53, 2013, pp. 184 – 195

[68] Mole G., "Improved methods of test for the insulation of electrical equipment", Proceedings of IEE, Vol. 100, part IIA, 1953, pp. 276 – 283

[69] Starr W. T., "Detection of corona discharges in lamped circuit specimens",Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 101 – 133

[70] Pearmain A. J. Danikas M. G., "A study of the behavior of a uniaxially oriented polyethylene tape/oil insulating system subjected to electrical and thermal stresses", IEEE Transactions on Electrical Insulation, Vol. 22, No. 4, 1987, pp. 373 – 382

[71] Bruning A. M., Danikas M. G., "Observations on discharges above and below CIV in polymer insulation", Annual Report on Conference of Electrical Insulation and Dielectric Phenomena (CEIDP), 20-23 October, 1991, Knoxville, Tennessee, USA, pp. 638 – 647

[72] Bruning A. M., Danikas M. G., "Report on continuing work on parallel and non-parallel electric field chemical aging of polymer cavities", Proceedings of the 4th International Conference on Conduction and Breakdown in Solid Dielectrics, 22-25 June, Sestri Levante, Italy, 1992, pp. 241 – 245

[73] Danikas M. G., "On the damage of insulating materials below inception voltage", Journal of Electrical Engineering, Vol. 52, No. 11-12, 2001, pp. 367 – 371

[74] Harlin A., Danikas M. G., Hyvonen P., "Polyolefin insulation degradation in electrical field below critical inception voltages", Journal of Electrical Engineering, Vol. 56, No. 5-6, 2005, pp. 135 – 140

[75] Danikas M. G., Zhao X., Cheng Y., "Experimental data on epoxy resin samples: Small partial discharges at inception voltage and some thoughts on the existence of charging phenomena below inception voltage", Journal of Electrical Engineering, Vol. 62, No. 5, 2011, pp. 292 – 296

[76] Moraru D., Popesco C., Stoica M., Tanasesco F., "Detection of degradation produced by partial discharges in paper-oil insulation", CIGRE report, paper 15-05, 1970, pp. 1 – 8

[77] Suwarno S., Mizutani M., "Pulse-sequence analysis of discharges in air, liquid and solid insulating materials", Journal of Electrical Engineering and Technology, Vol. 1, No. 4, 2006, pp. 528 – 533

[78] Joyo T., Okuda, T., Kadota N., Miyatake R., Okada S., Mio K., "Phase resolved partial discharge patterns for various damage of winding insulation Detected with different measuring devices", Proceedings of the 2017 Electrical Insulation Conference (EIC), June 11-14, 2017, pp. 344 – 347

[79] Ilias H., Soon Yan T., Abu Bakar A. H., Mokhlis H., Chen G., Lewin P. L., "Partial discharge patterns in high voltage insulation", Proceedings of the 2012 IEEE International Conference on Power and Energy (PECon), December 2-5, 2012, Kota Kinabalu Sabah, Malaysia, pp. 750 – 755

[80] Endharta A. J., Kim J., Kim Y., "Online partial discharge measurement for condition-based maintenance of HV power cables in railway infrastructure", Journal of Engineering and Management in Industrial System, Vol. II, No. 1, 2023, pp. 54 – 59

[81] Liao R., Yan J., Yang L., Zhu M., Liu B., "Study of the relationship between damage of oil-impregnated insulation paper and evolution of phase-resolved partial dis-charge patterns", European Transactions on Electrical Power, Vol. 21, 2011, pp. 2112 – 2124

[82] Nair R. P., Vishwanath S. B., "Analysis of partial discharge sources in stator insulation system using variable excitation frequency", IET Science, Measurement and Technology, Vol. 13, No. 6, 2019, pp. 922 – 930

[83] Negara M. Y., Fahmi D., Asfani D. A., Hernanda G. N. S., Soebagio J. C., Siahaan V. Y., "Characteristics of partial discharge inception voltage patterns using antenna in air insulation", Proceedings of the 2020 12th International Conference on Information Technology and Electrical Engineering (ICITEE), October 6-8, 2020, Yogyakarta, Indonesia, pp. 263 – 268

[84] Lee C.-Y., Purba N., Zhuo G.-L., "Defects classification of hydro generators in Indonesia by phase-resolved partial discharge", Mathematics, Vol. 10, 2022, total number of pages 27 "https://doi.org/10.3390/math10193659"

[85] Danikas M. G., "The definitions used for partial discharge phenomena", IEEE Transactions on Electrical Insulation, Vol. 28, No. 6, 1993, pp. 1075 – 1081

[86] Danikas M. G., "Small partial discharges and their role in insulation deterioration", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 4, No. 6, 1997, pp. 863 – 867

[87] Verhaart H. F. A., van der Laan P. C. T., "Fast current measurements for avalanche studies", Journal of Applied Physics, Vol. 53, No. 3, 1982, pp. 1430 – 1436

[88] Danikas M. G., van der Laan P. C. T., "Fast measurements of partial discharge currents in solid dielectric samples containing voids", Conference Record of the 1988 IEEE International Symposium on Electrical Insulation, June 5-8, Boston, MA, USA, 1988, pp. 250 – 252

[89] Shafiq M., Kiitam I., Kauhaniemi K., Taklaja P., Kutt L., Palu I., "Performance comparison of PD data acquisition techniques for condition monitoring of medium voltage cables", Energies, Vol. 13, 2020, total number of pages 14 "https://doi.org/10.3390/en13164272"

[90] Lemke E., "A critical review of partial discharge models", IEEE Electrical Insulation Magazine, Vol. 28, No. 6, 2012, pp. 11 - 16

[91] Kartalovic N., Kovacevic D., Milosavljevic S., "An advanced model of partial discharge in electrical insulation", Facta Universitatis, Ser: Electronics and Energetics, Vol. 24, No. 1, 2011, pp. 41 – 55

The Overall Antenna Bandwidth with an Application to the Improved Study of Radial Discone

N.I. Yannopoulou, P.E. Zimourtopoulos

Antennas Research Group, Austria - www.op4.eu

Abstract

Broadband antenna characterization is usually referenced implicitly to SWR bandwidth, which is often reported to have an unrealistically huge value without consideration of any other antenna property. The definition of the Overall Antenna Bandwidth is introduced in order to generalize the broadband characterization to include simultaneous broadband antenna properties - in our classification: field, circuit, or field-circuit - needed in practical situations. As an application, a radial discone antenna, i.e. a radial outline of the well-known broadband discone, was studied computationally, for its broadband operation improvement. Simulation was performed using the [RichWire] program. To adequately serve UHF non-GPS wireless 50 Ohm applications, normal/tight criteria were imposed on appropriate antenna properties for their value variations. The resulted bandwidths of 4:1 for horizontal directivity/power gain greater than –3dB (field), 6:1 for mismatch loss ML greater than –0.5 dB or SWR less than 2 (circuit), and 4:1 for horizontal radiation intensity greater than –3dB (field-circuit), define a simultaneous broadband operation in 800-3000 MHz. Web animations demonstrate the results of the generalized broadband antenna characterization using the definition of the overall antenna bandwidth.

Keywords

Broadband antennas, overall antenna bandwidth, wireless applications, antenna simulation

Introduction

Broadband antennas can be used, among others, in wireless applications where still a large number of bands lie above 800 [MHz] [1], [2], in

UHF. Simple wire (or patch) loaded monopole disc antennas for multi-broadband wireless applications were proposed by Suh et al. in 2003. However, from the just three given radiation patterns concluded that there are low normalized radiation intensity values (band-gap), of the order of –20 to –30 dB, from ~2000 [MHz] to ~2400 [MHz] operating sub-bands [3]. Notably, this behavior of low SWR in connection with high band-gaps is observed in the work of Kim et al. who presented an extraordinary ultra-wide band 100:1 Double Discone Antenna With the Tapered Cylindrical Wires but with radiation intensity band-gaps [4].

Observing the practical deviation between high broadband SWR characteristics and radiation band gaps we unified the circuital and field properties in the broad bandwidth formation of an antenna by introducing the definition of the overall antenna bandwidth. This definition was then applied to design a simple variation of the discone – a radial discone antenna – for wireless applications from copper wire fed by an N-type female connector for operation from 800 to 3000 [MHz] [5], and can be used as a guide.

An extensive investigation has been carried out for the radial discone antenna that covered: 1) the possible cone flare-angles from 15° to 180°, 2) three different values of the gap between the disc and the cone part of the antenna which proved to be a very important parameter and 3) two different values for the disc diameter.

Simulation was based on a suite of developed by us visual tools supported by a fully analyzed, corrected and redeveloped edition of the original thin-wire computer program by J.H. Richmond [6].

Broadband definition

First of all, we downgrade the common, currently in use, definition of "antenna bandwidth", to what it really is, that is as its "SWR-bandwidth" only. Next, in order to form the Overall Bandwidth of an Antenna by taking into account any number N of its frequency dependent properties Q_i, $1 \leq i \leq N$, we like, we give the following definition of Q-Bandwidth of any Q of these Q_i:

If a frequency dependent antenna property Q is mathematically expressed by a real valued function of frequency f, that is as: $Q = Q(f)$ or by $Q : \mathbb{R}_+ \to \mathbb{R}$ and we want to get the interval of Q property values $I_Q = [Q, Q'] \subset \mathbb{R}_+$, then the Q-bandwidth Q-BW can be always defined as the set of f frequency values for which the Q has values between Q and Q', or as the inverse image of I_Q by Q: $Q\text{-}BW = Q^{-1}[I_Q]$.

This definition stands for any real quantity, i.e., the norm of a vector function, the dimensionless quantities for example those expressed in dB, for the real or imaginary part of impedance or the magnitude of impedance. It is possible to be used even for complex "quantities", if we combine it with the concept of the circular region in $\mathbb{C}$.

Notably, the theoretically resulting Q-BW set of frequencies may happen to be any subset of $\mathbb{R}$, e.g. a single frequency, a number of frequencies, a finite interval of frequencies, a combination of them, or even the whole $\mathbb{R}_+$, or the empty set $\emptyset$. But, in practice, since the operating frequencies of the source feeding the antenna are just those representable by rational numbers with a given finite length of digits, the domain of function Q is just a subset of a finite interval [f, f'], so the same will be hold for the Q-BW itself, it will be just a subset of this practically well-known set of operating frequencies.

After that, for more than one antenna properties, that is for Q_i quantities with $1 \le i \le N$, we define the Overall Antenna Bandwidth as the common intersection of all Q_i bandwidths:

$$\bigcap_i Q_i = Q_1 \cap Q_2 \cap \ldots \cap Q_N \tag{1}$$

In this study, three quantities were selected, the usually most interesting in antennas, in order to estimate the bandwidth of the examined radial discone antennas, as an attempt to quantify their broadband property. These Q_i are:

a) Q_1: the 50-Ω Voltage Standing Wave Ratio SWR, as the most common used circuit characteristic,

b) Q_2: the Power Gain G_p at the horizontal plane where $(\theta = \pi/2, \varphi)$, as the field property and

c) Q_3: the Radiation Intensity U at the horizontal plane, as the mixed circuit-field characteristic.

To avoid excessive repetition of theory we consider as granted that $Z = R + i\,X$ as input impedance and G_p as power gain are the given output of Thin-Wire (RichWire) computer program via simulation, Z_0 the characteristic impedance and $\dot{V}_s$ the input source voltage. Then the radiation intensity is given [7 – 9] by

$$U(\theta,\varphi)=\frac{1}{4\pi}|\dot{V}_s|^2 G_p(\theta,\varphi)\frac{R}{(R+Z_0)^2+X^2}$$

$$=\frac{1}{4\pi}\frac{|\dot{V}_s|^2}{4Z_0}G_p(\theta,\varphi)\frac{4}{2+SWR+\frac{1}{SWR}} \quad (2)$$

Discone and Simulation

The design parameters of a discone (more exactly, a disc over a frustum cone) is shown in Fig. 1, where D is the disc diameter (t is its radius), d is the small (upper) diameter of the frustum cone, C is the large (lower) diameter of the frustum cone, s is the slant height, a is the flare-angle and g is the spacing (gap) between disc and cone. While this antenna was an invention of Kandoian [10], the first design relations was given by Nail [11]:

$$s = u\,(\lambda_1/4),\ D = v\,C,\ g = w\,d \quad (3)$$

where λ_1 is the wavelength at the lowest "operating frequency" f_1, and the parameters are:

$$u = 1,\ v = 0.7,\ w = 0.3 \quad (4)$$

It is worth mentioning that Nail also stated the following hypothesis: "although no investigation has been made, it appears that the larger flare-angle discones (a ≥ 90°) give better performance in the horizontal plane over large frequency bands than the smaller-flare-angle discones".

Later Rappaport designed discones using an N-type male connector feed and suggested other values for the parameters [12]:

$$u = 1.15,\ v = 0.75,\ w = 0.5 \quad (5)$$

The implementation of the discone antenna outline with wire radials may be called, among other names, a "radial discone" and Cooke observed that the following u parameter value is more appropriate for such antennas [13]:

$$u \approx 1.33 \quad (6)$$

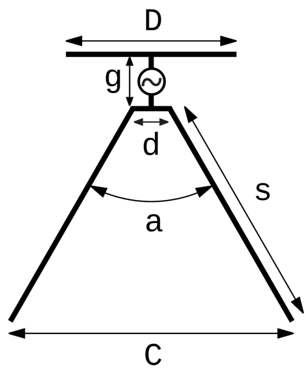


Fig. 1: Discone antenna

Although there are authors proposed different, rather slight, modifications on the parameter values, those of (3)-(5) may considered as the most accepted ones.

Additionally, since the lower f_1 and upper f_2 "broadband" frequency limits result as the most distant frequencies for which a designer-selected quantity is bounded between two designer-selected values, it is not possible to have in advance a guaranteed broadband zone. These facts keep open the discone and radial discone investigation of which the $[f_1, f_2]$ zone is rather an unknown result than a given datum.

To the best of authors' knowledge:

(a) The radial discone antenna study is more or less experimental and there is no systematic study, which combines analysis, simulation, construction and measurements.

(b) There is no definite value for the flare-angle, of either radial or ordinary discone, other than the one resulting from the obvious trigonometric relation:

$$C = 2s \sin(a/2) \quad (8)$$

(c) The broadband characterization is given usually by circuital SWR, while the radiation properties of the antennas are either neglected or limited to pattern illustrations in a number of spot frequencies into the claimed bandwidth. Thus, if the main interest is for a base station scanner antenna, with omnidirectional radiation pattern near-by the horizontal plane, as in the case of [14], care must be taken in order to achieve a rather constant radiation pattern.

d) For applications such as wireless communication, with the demand for operation on an increased frequency band there is a need for an upper operation frequency directive.

A visual program was specifically developed to design a broadband radial discone with bare wires embedded in free space when the wire conductivity, the type of feeding connector and the frequency band are given. Constructional details of the used technique have been given analytical in [15].

The consideration of radial discone as an array of at least 8 V-dipoles produces a theta-polarized vector radiation pattern with magnitude a surface almost by revolution around z-axis. So the radial discone has indeed on horizontal plane xOy the basic properties of a vertically polarized almost omni-directional antenna, a fact that encouraged design of a broadband model by simulation. The model that was used for the simulation is shown in Fig. 2.

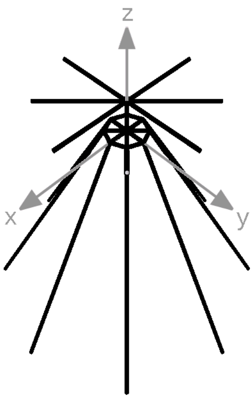


Fig. 2: Disc-Frustum Cone radial discone model

A unified study of any radial discone may be considered as parallel to the one of the following application: A constant slant height as $\lambda_1/3$, at the lowest desired frequency of 800 [MHz] that is 12.5 [cm], (equal to $\lambda/4$ at 600 [MHz]) and constant small cone diameter d equal to the N-type female connector diameter, 1.6 [cm] were considered. Three parameters were variable:

(a) The cone flare angle a in the range [15°, 180°] in steps of 15°.

(b) The disc diameter D with two v values as Nail (0.7 C) and Rappaport (0.75 C) proposed.

(c) The disc to cone distance g with three values: 3 mm as the minimum possible one, 6 mm approximately equal with that of (3) (~5 mm) and 8 mm as (4) suggests. Thus, there are 6 possible antenna models for each different cone flare angle.

Three arithmetic criteria were adopted for the broadband characterization of a model, as mentioned above:

a)the 50-Ω SWR is lower than 2, $Q_{SWR} = Q_1$: SWR ≤ 2 or similarly the mismatch loss is greater than –0.5 dB, –0.5 dB ≤ ML, where ML = $10\log_{10}(1-\rho^2)$ with ρ the reflection coefficient,

b) the relative Directivity Gain G_d, or Power Gain G_p, is greater than –3 dB on horizontal plane where $G_p = e\, G_d = G_d$ for performance coefficient $e \approx 1$, as it is considered for a perfect conductor, $-3\text{ dB} \le G_{dH} \approx G_{pH}$: $Q_2 = Q_{Gp}$ and

c) the normalized radiation intensity U/Umax = $\mathcal{U}$, is greater than –3 dB on horizontal plane, $-3\text{ dB} \le \mathcal{U}_H$: $Q_3 = Q_{\mathcal{U}}$.

As a practical application of the broadband design, the 2G/3G band from 800 to 2500 [MHz], extend below to 600 [MHz] to cover the case of λ/4 slant height, was selected to begin with. Six sub-bands introduced, I: 806-960 MHz, II: 1429-1513 MHz, III: 1710-1900 MHz, IV: 1910-2025 MHz, V: 2110-2170 MHz and VI: 2400-2499 MHz.

The 50-Ω SWR, the normalized radiation intensity on horizontal plane and the relative Power Gain on horizontal plane are shown in Figs. 3 - 8, for the $12 \times 6 = 72$ simulated models in the frequency range [600, 2500] MHz. The vertical gray strips indicate the six sub-bands, light (I, II, III) and dark (IV, V, VI) correspondingly. It is obvious that for flare angles less than 45° and greater than 120° the frequency range with $\text{SWR} \le 2$ is reduced, the radiation intensity and even more the power gain on the horizontal plane are rapidly decreased below −3dB with frequency, especially for the larger flare angles ($> 135°$). Therefore Nails claim, mentioned above, for better performance in the horizontal plane over large frequency bands of the larger flare-angle discones (a ≥ 90°) [11], which led on our research to cone flare angle greater than 90°, seems that it is not verified at least for radial discones. To validate this conclusion, Fig. 9 gives the maximum of 50-Ω SWR for all the simulated models in the considered frequency range while Fig. 10 and Fig. 11 give the minimum values of radiation intensity and power gain on the horizontal plane, respectively.

Results

Eighteen models were selected to be constructed with cone flare angles 60° (with the best performance), 90° (marginal case) and 120° (the greater cone angle with satisfactory characteristics) by applying the mixture of directives from (3)-(5), as was aforementioned. Analytic results will be presented in a forthcoming work.

In Fig. 12 (a)-(c) typical simulation radiation intensity 3D patterns are given for these antennas at the center of each sub-band, which confirm the horizontal omnidirectional radiation properties of the broadband models.

It is obvious from Figs. 3 - 11 that the better broadband performance, with respect to the three adopted criteria, was achieved by the 60° radial discones. Fig. 13 shows the horizontal mean value in [dB] versus the horizontal range between min and max value in [dB], for all the 72 simulated models. The magnified little rectangle in the upper left corner contains the four 60° radial discones with the best values.

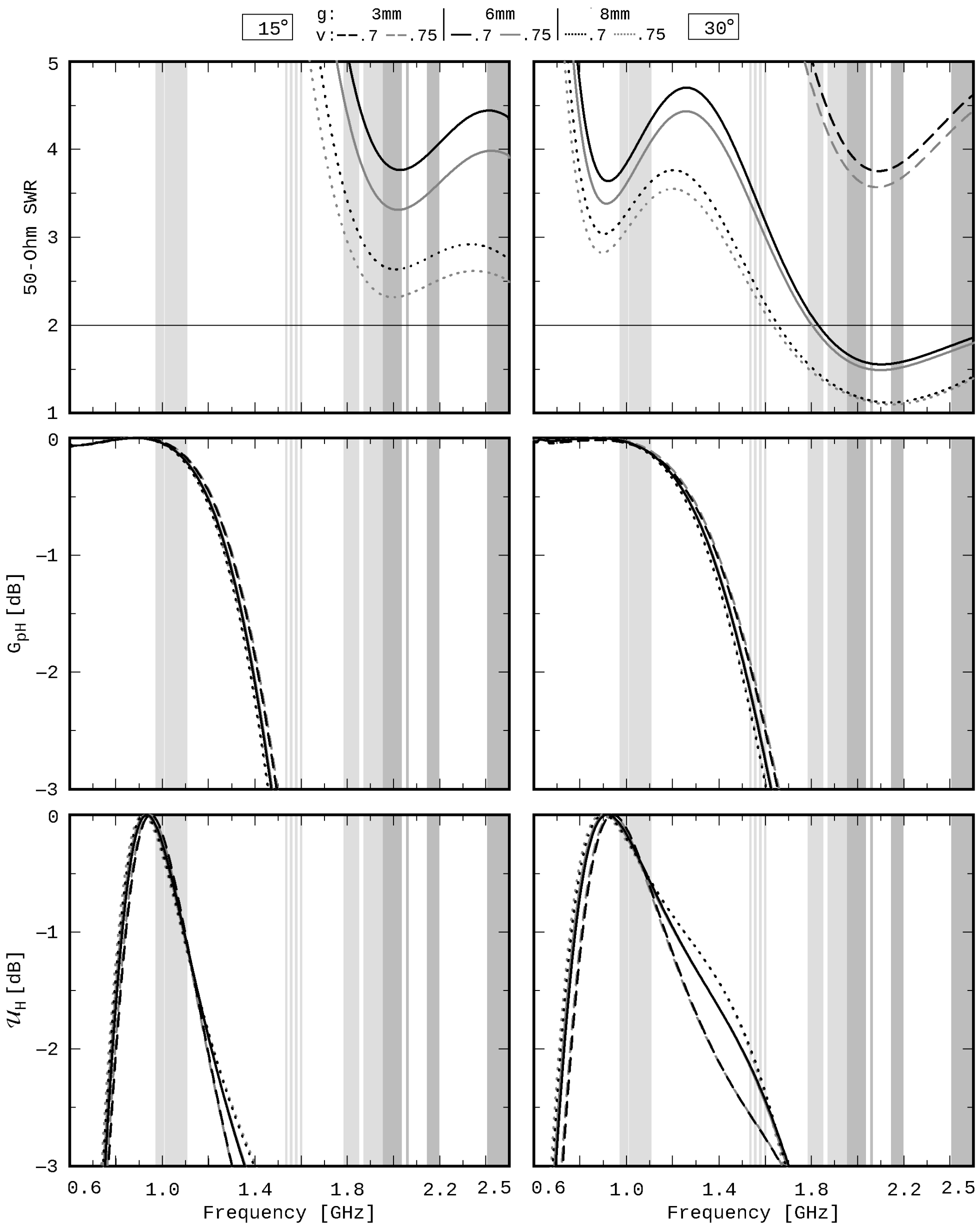


Fig. 3: SWR, G_{pH}, $\mathcal{U}_H$ for a = 15° and a = 30°

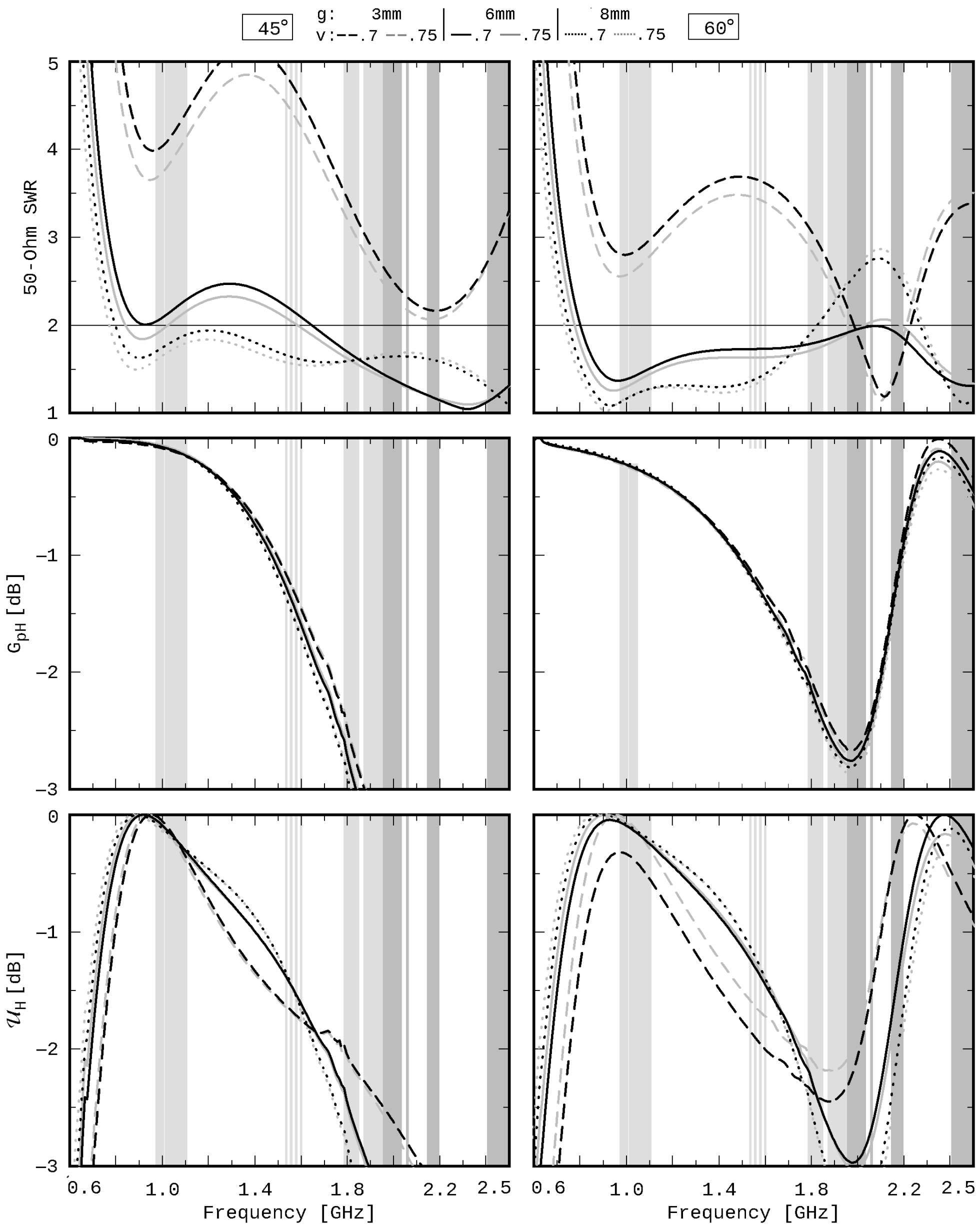


Fig. 4: SWR, G_{pH}, $\mathcal{U}_H$ for a = 45° and a = 60°

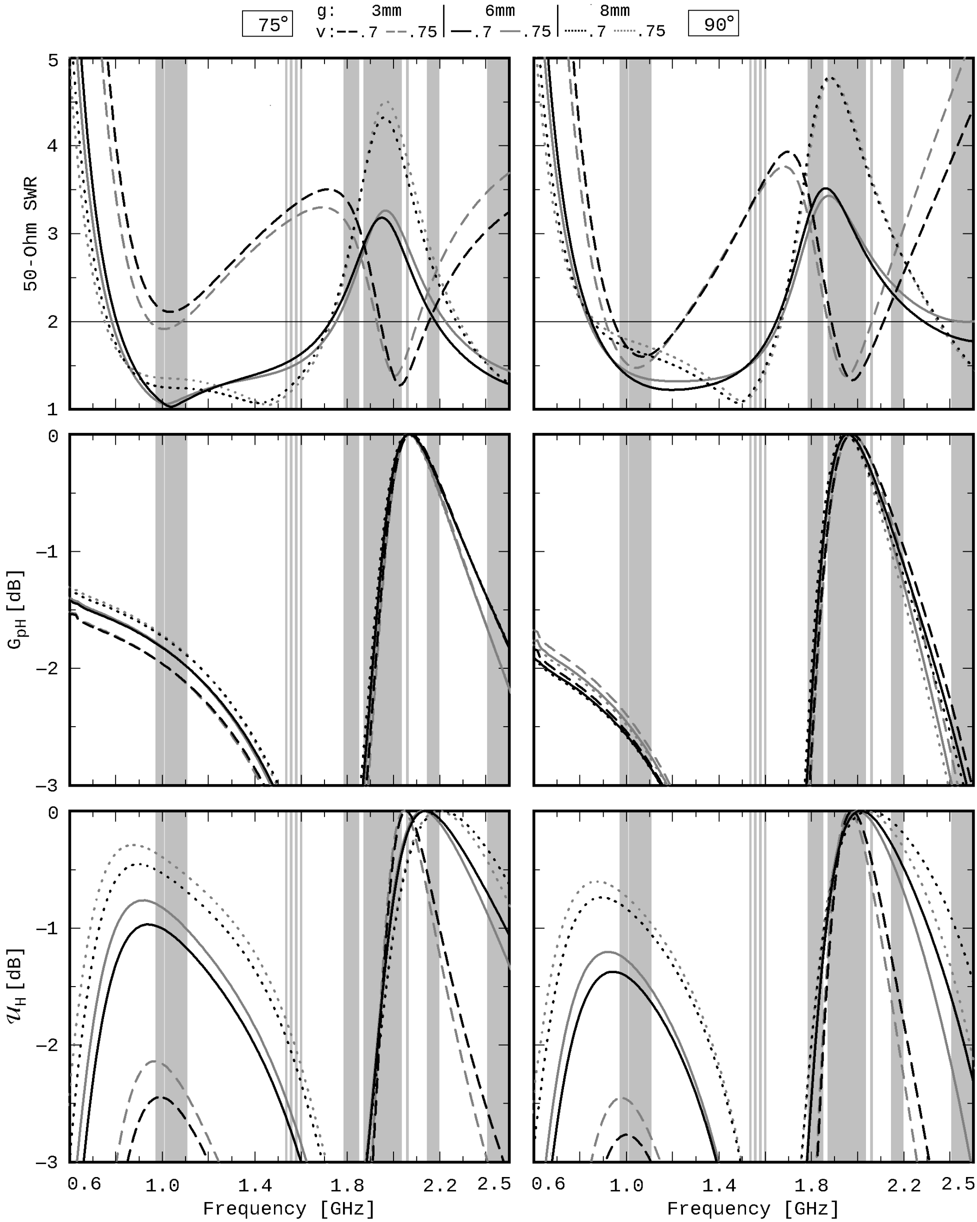


Fig. 5: SWR, G_{pH}, $\mathcal{U}_H$ for a = 75° and a = 90°

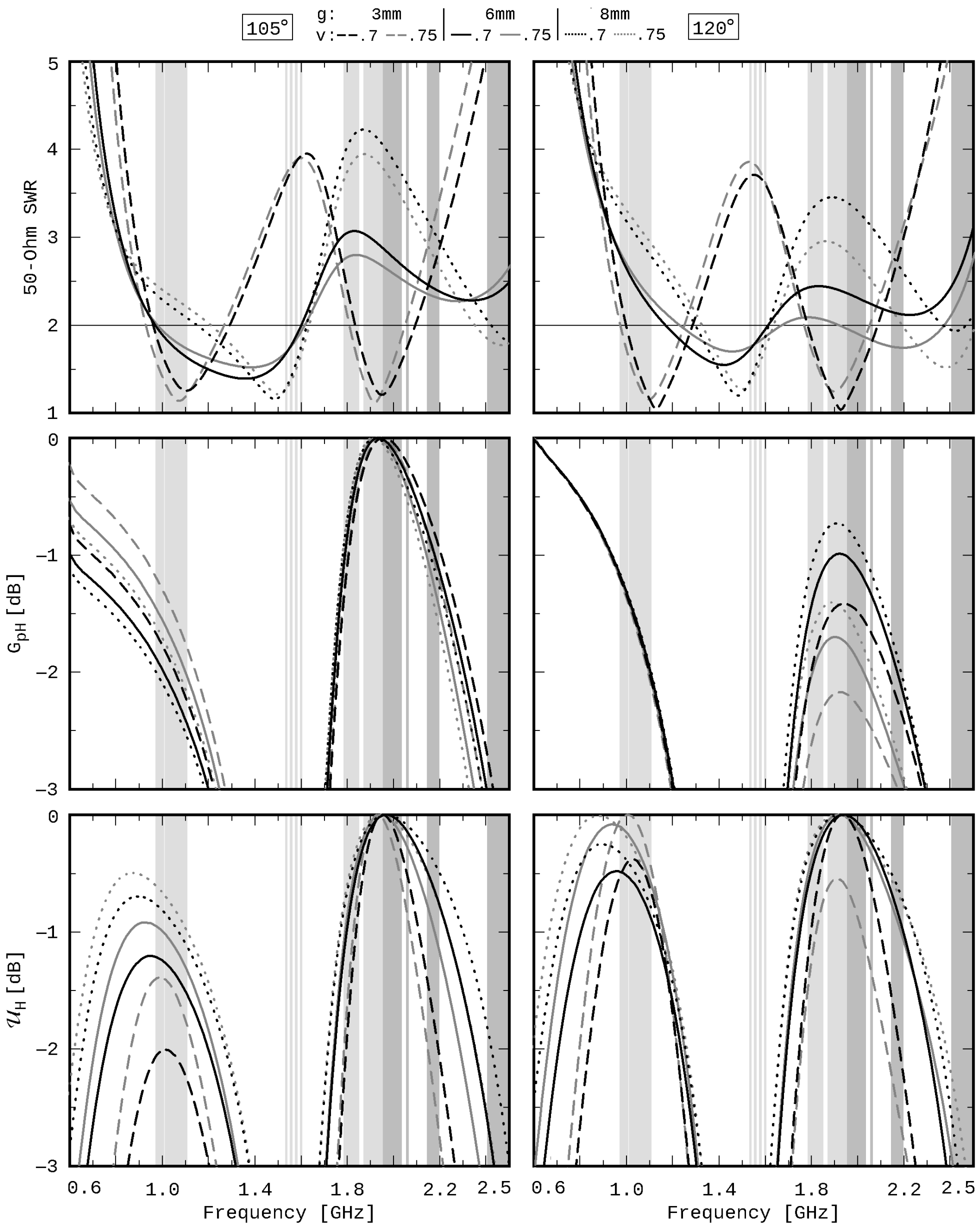


Fig. 6: SWR, G_{pH}, $\mathcal{U}_H$ for a = 105° and a = 120°

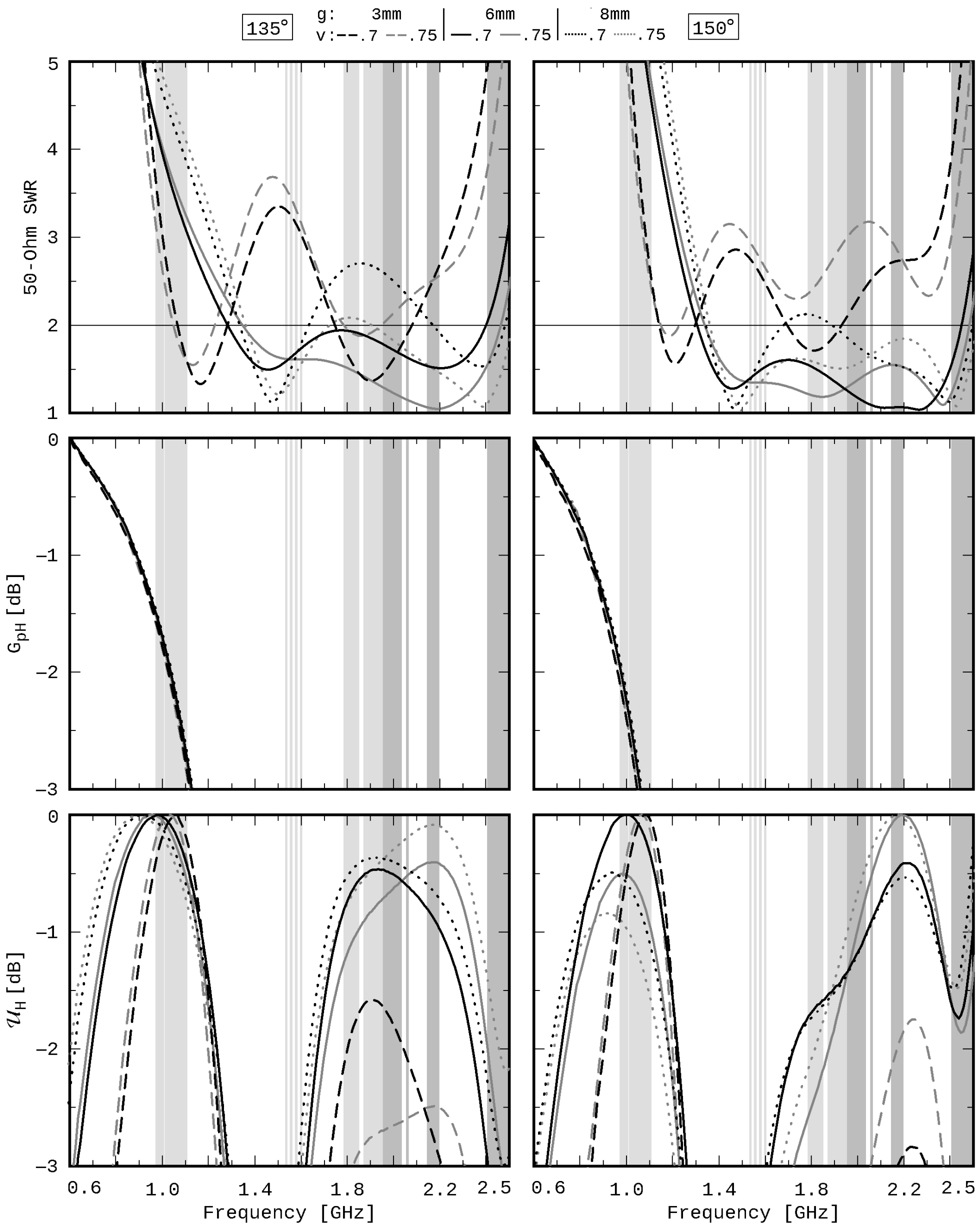


Fig. 7: SWR, G_{pH}, $\mathcal{U}_H$ for a = 135° and a = 150°

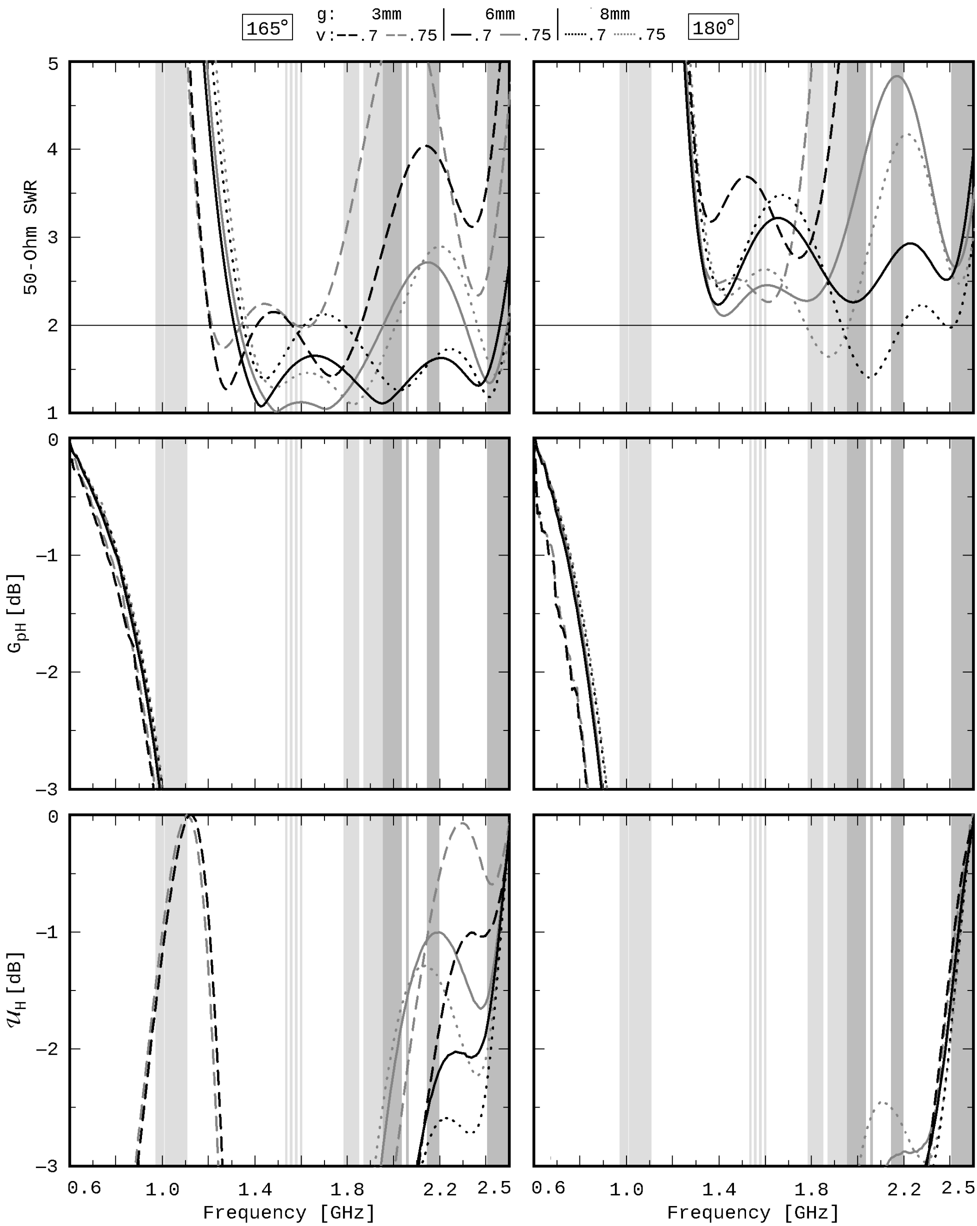


Fig. 8: SWR, G_{pH}, $\mathcal{U}_H$ for a = 165° and a = 180°

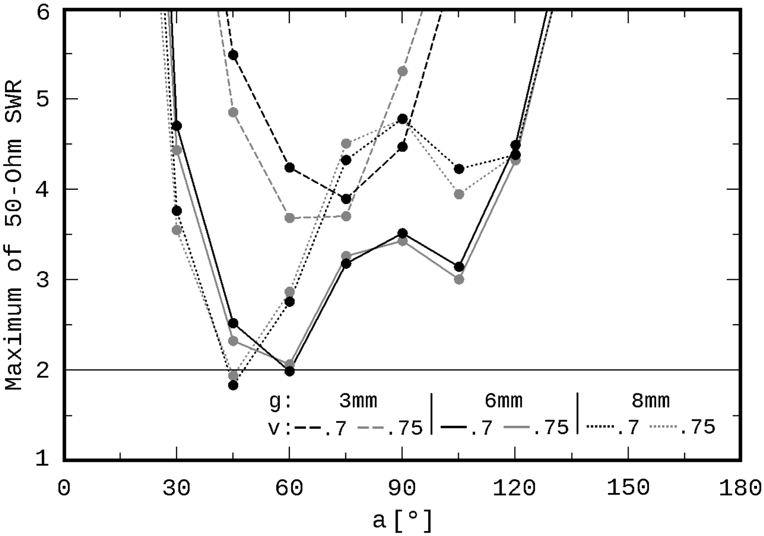


Fig. 9: Maximum 50-Ω SWR of overall 600-2500 MHz

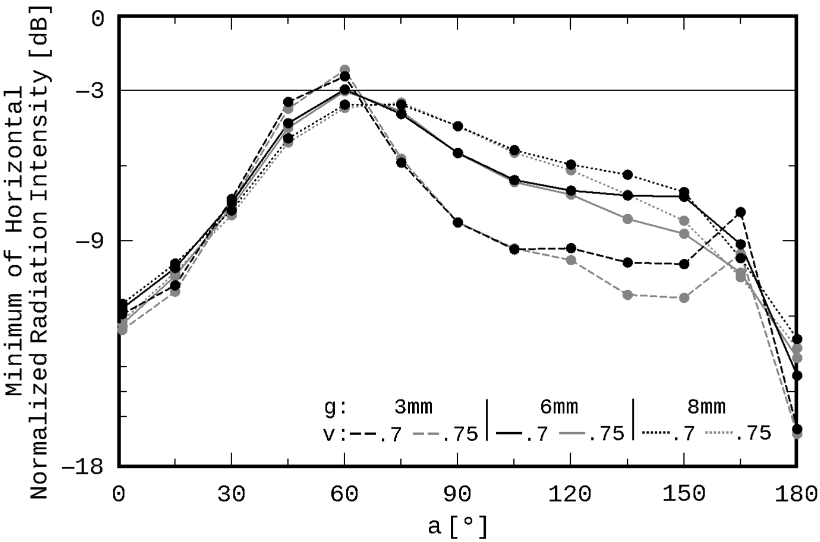


Fig. 10: $\mathcal{U}_{H}$ minimum values of overall 600-2500 MHz

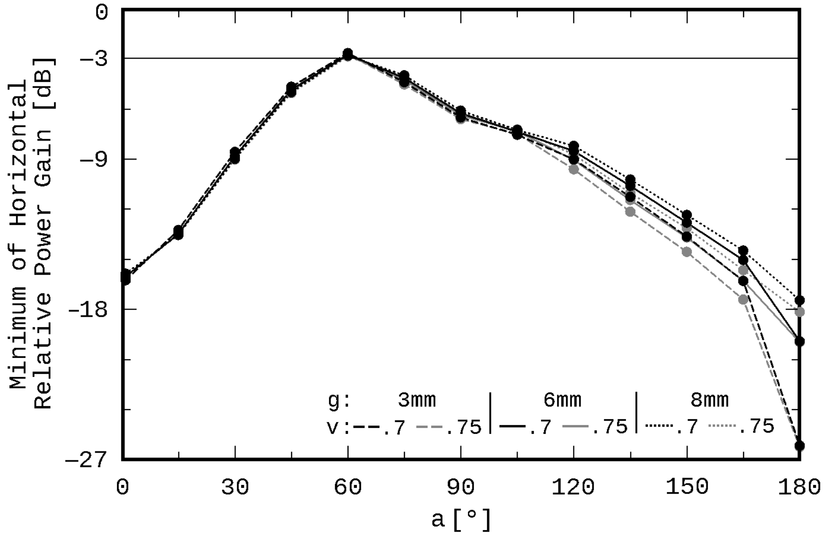
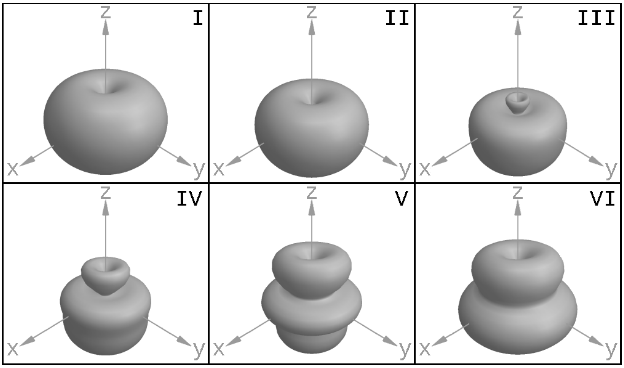


Fig. 11: G_{pH} minimum values of overall 600-2500 MHz

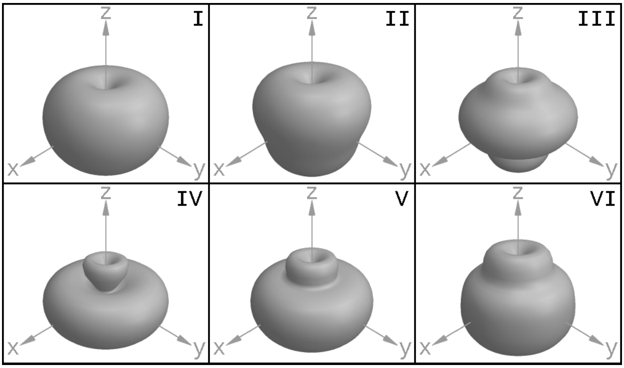
Their measured and simulated SWR with DERs (Differential Error Regions) as gray clouds are shown in Fig. 14 in separate frame for each antenna with its dimensions.

Thus, the application of the broadband criteria for the selected frequency range resulted to the design of radial discone, model 3 in Fig. 13 and Fig. 14, with D = 8.8 [cm], g = 0.6 [cm], s = 12.5 [cm], d = 1.6 [cm] and a = 60° which operates from 800 to 3000 [MHz], exceeding the initial range and it was initially presented in [5], yet using only two criteria. Fig. 15 shows the analytical predicted, simulated and measured radiation intensity on a vertical plane at the center frequency of the measurement band, at 950 [MHz], with a good agreement. Fig. 16 shows the reflection coefficient in the smith chart for this antenna, from simulation and measurement with the DERs as gray cloud for the measurement band. The small open circular points indicate the corresponding explicitly given frequencies.

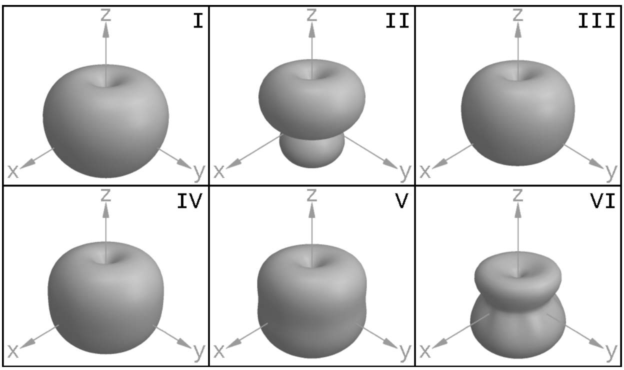
In order to test the limits of this antenna Fig. 17 shows its Directivity while Fig. 18 shows the four quantities of $\mathcal{U}$, SWR, G_p and mismatch loss ML at the extended frequency band from 300 to 6000 [MHz].



(a) 120°



(b) 90°



(c) 60°

Fig. 12: Predicted normalized radiation intensity patterns at the center of each sub-band for 120°, 90° and 60° flare-angles

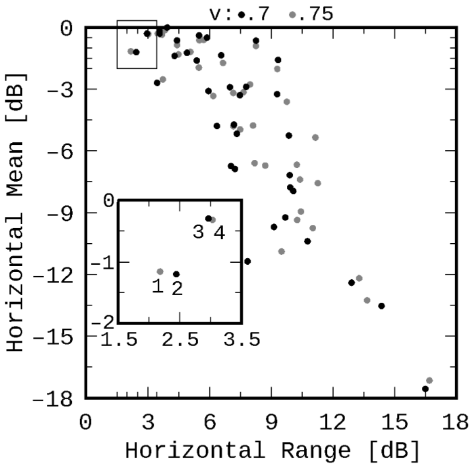


Fig. 13: Horizontal mean and range values for all 72 simulated models

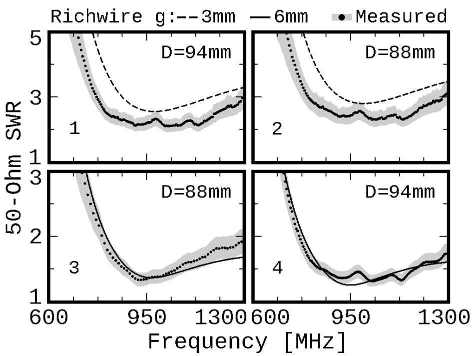


Fig. 14: Four antennas - measured and simulated SWR

The resulted bandwidths of 6:1 for ML ≤ 0.5 dB or SWR ≤ 2 and 4:1 for −3 dB ≤ $G_{dH} \approx G_{pH}$ and 4:1 for −3 dB ≤ $\mathcal{U}_H$ considered continuously excluding the frequency gaps, proved the successful design of the selected radial discone antenna as a broadband antenna with almost omnidirectional antenna pattern on the horizontal plane for the whole band 800 to 3000 [MHz] by applying the introduced generalized broadband characterization.

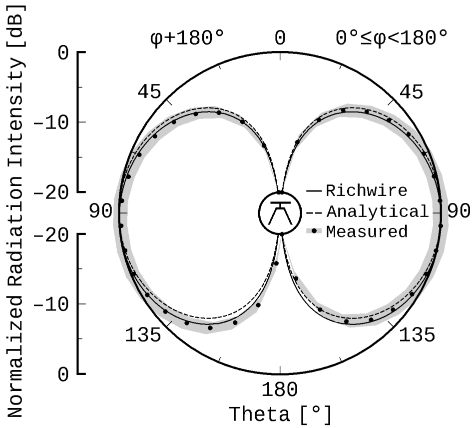


Fig. 15: $\mathcal{U}$ pattern on a vertical plane at 950 [MHz]

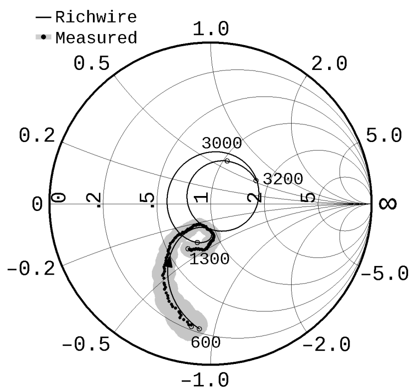


Fig. 16: ρ̇ in the Smith chart

Tab. 1 contains the frequency intervals where the three considered criteria are satisfied and their corresponding Q_i bandwidths while in Fig. 19 the resulted Q-BW is shown, as their intersection.

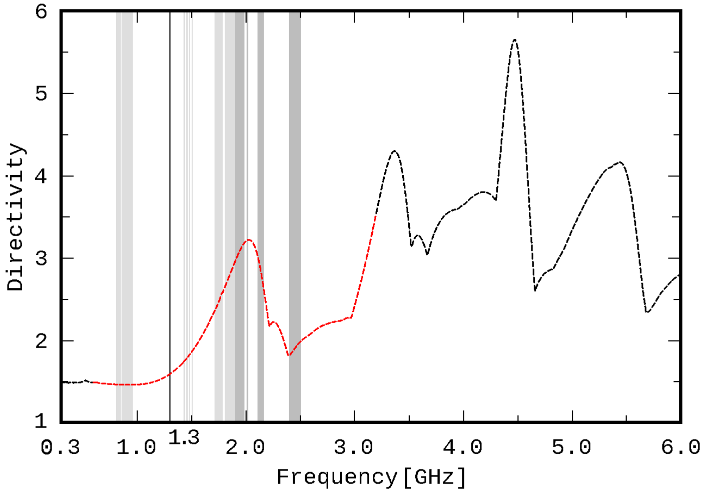


Fig. 17: Directivity at the extended frequency band

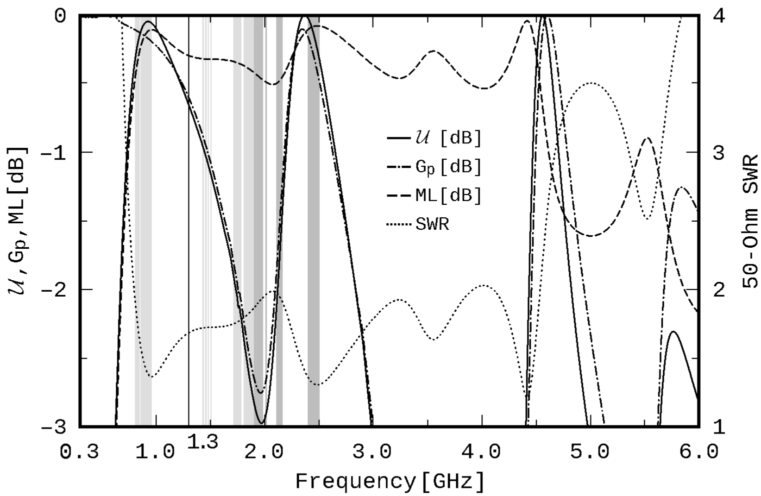


Fig. 18: $\mathcal{U}$, SWR, G_p and ML at the extended frequency band

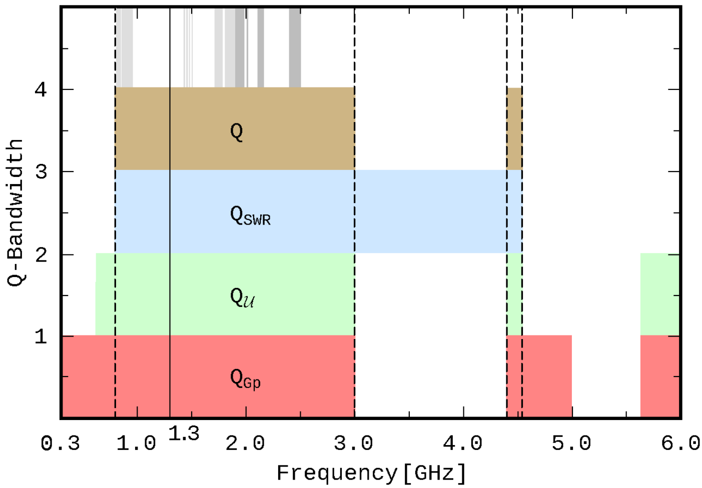


Fig. 19: Q-BW as intersection of Q_{SWR}, Q_{Gp} and $Q_{\mathcal{U}}$ bandwidths

Tab. 1: Q_i bandwidths

<table>
<tr><th></th><th>Q_i [MHz]</th><th>Q-BW = $\cap Q_i$</th></tr>
<tr><td>Q_{SWR}</td><td>[800, 4540]</td><td rowspan="3">[800, 3000]
$\cup$
[4400, 4540]</td></tr>
<tr><td>Q_{Gp}</td><td>[300, 3000]$\cup$[4400,4980]$\cup$[5640, 6000]</td></tr>
<tr><td>$Q_{\mathcal{U}}$</td><td>[630, 3000]$\cup$[4400,4980]$\cup$[5640, 6000]</td></tr>
</table>

Conclusion

During the investigation procedure an extended study of the radial discone antenna behavior for various flare angles, lower and higher of 60°, from 15° to 180° was performed.

To the best of the authors' knowledge it was the first time that data are presented for discones with flare angle a ≥ 90°, and such antennas were constructed and measured, although it was proved that the typical 60° antenna had the best performance for the purpose that have been set. All the measurements were performed according the presented previous authors' work [15] - [17].

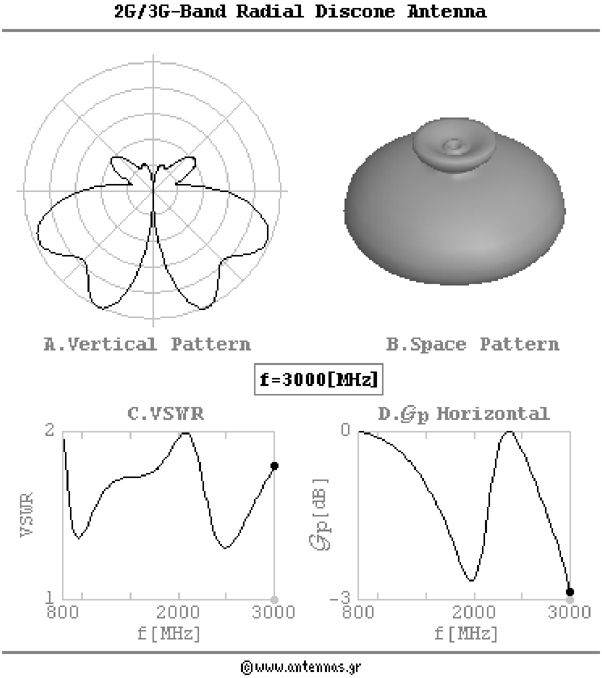


Fig. 20: 2D and 3D $\mathcal{U}$ pattern, SWR and G_{pH}

Unfortunately, Nail's claim in 1953 for better performance in the horizontal plane of discones with larger flare angles for broader frequency ranges than the smaller flare angles was not proved to be true, at least for their radial version. For instance the radial discones with 150° and 30° flare angle have both a low SWR but in a narrower frequency range and the most essential their pattern on the horizontal plane is almost zero for significant large sub-bands. In Fig. 7 although the 150° discone seems to be better for $\mathcal{U}_H$ than the discone with 30° flare angle in Fig. 3, this is not true since its horizontal gain G_{pH} is much worse. In the same time the slant height dimension as λ/3 at the lowest desired frequency of Cooke was justified.

The generalized broadband characterization of an antenna introduced here as the "Overall Antenna Bandwidth", combines for the specific application three quantities of different nature with the following demands:

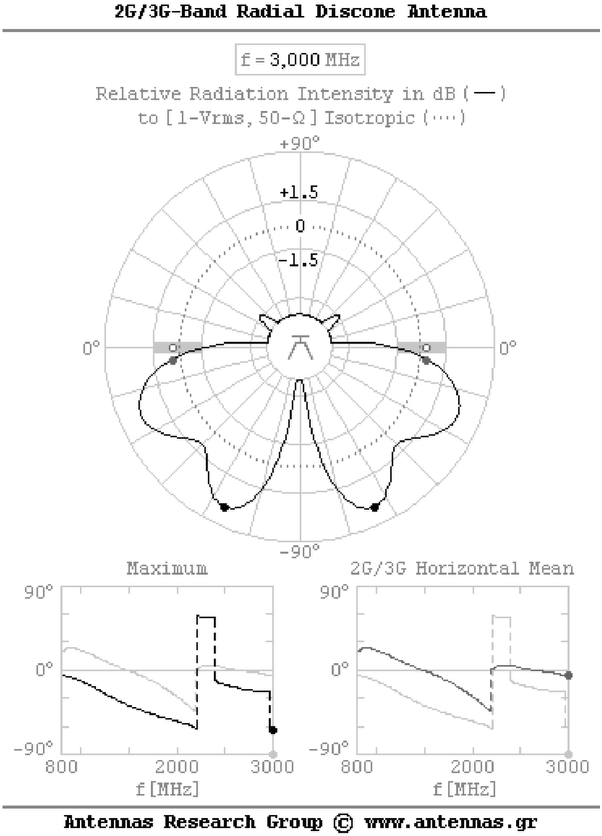


Fig. 21: 2D $\mathcal{U}$ pattern, direction of maximum and horizontal mean value

a) SWR (circuit quantity)

Q_{SWR}: SWR ≤ 2

b) the horizontal directivity/power gain G_{dH}/G_{pH} (field quantity)

Q_{Gp}: −3dB ≤ G_{pH}

c) the horizontal radiation intensity $\mathcal{U}_H$ (field - circuit quantity)

$Q_{\mathcal{U}}$: −3dB ≤ $\mathcal{U}_H$

Thus, the overall bandwidth results as

$$\text{Q-BW} = Q_{SWR} \cap Q_{Gp} \cap Q_{\mathcal{U}}$$

It was proved that a successful design of such an antenna is possible. Two animations was prepared for the proposed radial discone antenna from which the last frames are shown in Fig. 20 and Fig. 21 respectively. The $\mathcal{U}$ pattern on a vertical plane, the corresponding 3D patter, the SWR and the power gain G_p in the horizontal plane are given in Fig. 20. In Fig. 21 the $\mathcal{U}$ pattern in [dB] is compared with that of an Isotropic antenna. The grey and black points indicate the directions of mean value in horizontal plane and maximum value respectively, which are shown below with respect to frequency. The produced animations and all other updated material will be available in the authors' website [18].

Full results of the constructed and measured models as well as some details for their fixed construction and the performed analytical study will be presented by the authors as an extended report in a future paper, as well as a full description of the developed software for the radial discone antenna.

References

[1] "Wireless Communication Standard", Register is required "https://www.rohde-schwarz.com/at/loesungen/test-and-measurement/wireless-communication/wireless-5g-and-cellular/wic-frequency-poster-sign-up_233688.html"

[2] Hashimoto A., Yoshino H. and Atarashi H., "Roadmap of IMT-Advanced Development", IEEE Microwave Magazine for the Microwave & Wireless Engineer, Vol. 9, No. 4, August 2008, pp. 80 - 88

[3] Suh S.Y., Stutzman W.L. and Davis W.A., "Multi-broadband monopole disc antennas", Antennas and Propagation Society International Symposium, IEEE, Vol. 3, 2003, pp. 616 - 619

[4] Kim K.H., Kim J.U. and Park S.O., "An Ultrawide-Band Double Discone Antenna With the Tapered Cylindrical Wires", IEEE Transactions on Antennas and Propagation, Vol. 53, No. 10, October 2005, pp. 3403 - 3406

[5] Yannopoulou N.I., Zimourtopoulos P.E., Sarris E.T., "All-Band 2G+3G Radial Disc-Cone Antennas: Design, Construction and Measurements", FunkTechnikPlus # Journal, Issue 1, Year 1, 2013, pp. 7 - 15 "www.ftpj.otoiser.org/issues/html/ftpj-issue-01-e4-lo4104-pdfc171-ia1.htm" (1-1)

[6] Richmond J.H., "Computer program for thin-wire structures in a homogeneous conducting medium", Publication Year: 1974, NTRS-Report/Patent Number: NASA-CR-2399, ESL-2902-12, DocumentID: 19740020595
"https://ntrs.nasa.gov/search.jsp?R=19740020595"

[7] Zimourtopoulos P., "Antenna Notes I 1999-, Antenna Design Notes II 2000-",(in Hellenic)
"https://www.antennas.gr/antennanotes/"

[8] Iliakis D., "Prototype Antenna ARG-01 'D-Dimond1'", Diploma Thesis #38, ARG—Antennas Research Group, DUTh, 2006 (in Hellenic), p. 3.25, Appendix Z
"https://www.antennas.gr/theses/diploma/arg-dt38.pdf"

[9] Yannopoulou N.I., "Study of monopole antennas over a multi-frequency decoupling cylinder", PhD Thesis, EECE, DUTh, February 2008 (in Hellenic), p. 3.13.5
"https://www.didaktorika.gr/eadd/handle/10442/20920?locale=en"

[10] Kandoian A.G., "Three New Antenna Types and Their Applications", Proceedings of IRE, Vol. 34, February 1946, pp. 70W - 75W

[11] Nail J.J., "Designing Discone Antennas", Electronics, August 1953, pp. 167 - 169

[12] Rappaport T.S., "Discone Design Using N-Connector Feed", IEEE Antennas and Propagation Society Newsletter, Vol. 30, February 1988, pp. 12-14Rappaport T.S., "Discone Design Using N-Connector Feed", IEEE Antennas and Propagation Society Newsletter, Vol. 30, February 1988, pp. 12 - 14

[13] Cooke D.W., "The Skeleton Discone", The ARRL Antenna Compendium, Vol. 3, 1993, pp. 140 - 143

[14] Scholz P., "Basic Antenna Principles for Mobile Communications", kathrein Antennen-Electronic, 2006, pp. 7, 11, 13
"http://www.hellsoft.cz/ok1ike/soubory/ant_txt/basicantenna.pdf"
"https://www.academia.edu/6053732/Basic_Antenna_Principles_for_Mobile_Communications"

[15] Yannopoulou N., Zimourtopoulos P., "Total Differential Errors in One-Port Network Analyzer Measurements with Application to Antenna Impedance", Radioengineering, Vol. 16, No. 2, June 2007, p. 1 - 8
"https://www.radioeng.cz/fulltexts/2007/07_02_01_08.pdf"

[16] Yannopoulou N., Zimourtopoulos P., "S-Parameter Uncertainties in Network Analyzer Measurements with Application to Antenna Patterns", Radioengineering, Vol. 17, No. 1, April 2008, pp. 1 - 8
"https://www.radioeng.cz/fulltexts/2008/08_01_01_08.pdf"

[17] Yannopoulou N., Zimourtopoulos P., "ANALYZE: Automated Antenna Measurements, ver. 13", Antennas Research Group, 1993 - 2008

[18] Yannopoulou N., Zimourtopoulos P., "Radial Discone Antenna Software and Other Material - Current Versions", "http://updates.ftpj.otoiser.org/files/35-2"

* Active Links: 30.09.2024 -
Reference Updates : FTP#J Link :
"https://updates.ftpj.otoiser.org/references/35-2"

[This Page Intentionally Left Blank]

ARG NfP AoI
Antennas Research Group
Not-for-Profit Association of Individuals [*]
www.arg.op4.eu — arg@op4.eu
Scheiblingkirchen, Austria

* The Constitution of Greece, Article 12(3) — 2008:
  www.hellenicparliament.gr/en/Vouli-ton-Ellinon/To-Politevma
* The Hellenic Supreme Court of Civil and Penal Law:
  www.areiospagos.gr/en — Court Rulings:Civil|A1|511|2008

FRONT COVER VIGNETTE

A faded synthesis of an anthemion rooted in a meandros

The thirteen-leaf is a symbol for a life tree leaf.
"Herakles and Kerberos", ca. 530–500 BC,
by Paseas, the Kerberos Painter,
Museum of Fine Arts, Boston.

www.mfa.org/collections/object/plate-153852

The simple meandros is a symbol for eternal immortality.
"Warrior with a phiale", ca. 480–460 BC,
by Berliner Maler,
Museo Archeologico Regionale "Antonio Salinas" di Palermo.

commons.wikimedia.org/wiki/File:Warrior_MAR_Palermo_NI2134.jpg