Response Time of Surge Protective Devices Employing Triggered Spark Gap Technology

Konstantinos M. Gektidis, *Student Member, IEEE*, Alexios I. Ioannidis, *Member, IEEE*, and Thomas E. Tsovilis, *Senior Member, IEEE*

***Abstract*—An experimental investigation of the sparkover performance of low-voltage surge protective devices employing triggered spark gap technology is made. The main goal of this study is the evaluation of the response time of three commercially available surge protective devices integrating spark gaps with gas mixture or atmospheric air, which are triggered through circuits employing resistors, metal-oxide varistors, and/or gas discharge tubes. Surprisingly, the experimentally derived response time varies beyond the upper limit (100 ns) declared by manufacturers; a variation of the response time from about 20 ns up to 20 μs is observed for a wide range of standard lightning and switching impulse voltages (2.0 kV–16.5 kV). The novelty of the study lies in i) the introduction of a response time definition for surge protective devices and ii) the proposal of a test method, that are both missing from the international standards. This work stresses the need for an update of the related standards to incorporate a definition of the response time of surge protective devices covering a wide range of transients also considering its statistical dispersion.**

***Index Terms*—Fast-front transients, slow-front transients, surge protection, trigger circuit, voltage switching component.**

I. Introduction

MODERN low-voltage grids employ sensitive electrical, electronic, and telecommunication equipment that is vulnerable to overvoltages and prone to failure due to lightning-related surges [1], [2], [3]. Thus, surge protection is vital to ensure the reliable and uninterrupted operation of power grids [4], [5], [6], [7]. Indicative of the importance of surge protection is that the annual cost of lightning-related damages to consumers in Germany is in the order of 200 M€ per year in the last decade according to the German Insurance Association [8]. Also, the National Fire Protection Association found that lightning is the cause of more than 40% of unexpected failures of low-voltage electronic equipment and that there were more than 250 thousand claims due to lightning damages in 2013 and 2014 [3]. These huge economic losses are expected to increase when considering that i) even more sensitive equipment will be integrated into smart cities' infrastructure and smart home devices [1], ii) the recorded lightning events are increasing as recently reported by VAISALA [9], and iii) modern cities utilize high buildings, which attract many lightning strikes [10].

Surge protective devices (SPDs) are commonly installed to low-voltage grids that integrate components of different materials and technologies, such as Metal-Oxide Varistors (MOVs), Transient Voltage Suppression (TVS) diodes, Gas Discharge Tubes (GDTs), and spark gaps [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. Actually, spark gaps, employing patented technologies [22], [23], [24], [25], are commonly used in SPDs and surge protection systems in Europe, despite their higher cost compared to varistors, thanks to the fact that they are able to i) handle surge currents of high energy content, ii) exhibit practically zero leakage current when not degraded, iii) effectively interrupt the power frequency follow current from the power grid after successful operation, iv) efficiently coordinate with secondary surge protection equipment, and v) maintain low let-through currents to the protected equipment, which is especially important for surge protection of sensitive equipment [26], [27], [28], [29].

Although extensive research has been conducted by industry and academia on the transient behavior of spark gap-based SPDs with a clear focus on the interruption of the excessive power frequency follow current [28], [29], [30], [31], the response time of spark gaps is rarely investigated and discussed in the literature [32], [33]. Furthermore, the UL 1449 [34] and the forthcoming IEC 61643-01 [35] and IEC 61643-41 [36] lack a definition of the response time of SPDs. An interesting analysis on the response time of SPDs has been provided in [37], [38], [39], covering, however, only varistor technology; nevertheless, this definition gives space for multiple interpretations of the response time as also pointed out by white papers of Schneider [40], General Electric [41], and Transtector [42]. The lack of a response time definition is an issue of high importance as longer response times may result in protected equipment damage, even when SPDs with appropriate protection levels and characteristics are selected. Actually, delayed response times could lead to direct exposure of the protected equipment to the lightning current [32].

In light of the above, it is evident that more research work is needed to address the following research gaps regarding the

Manuscript received 20 November 2022; revised 11 June 2023 and 9 October 2023; accepted 22 February 2024. Date of publication 27 February 2024; date of current version 21 May 2024. Paper 2022-PSPC-1294.R2, presented at the 2022 IEEE Industry Applications Society Annual Meeting, Nashville, TN, USA, Oct. 09–14, and approved for publication in the IEEE Transactions on Industry Applications by the Power Systems Protection Committee of the IEEE Industry Applications Society [DOI: 10.1109/IAS54023.2022.9939888]. *(Corresponding author: Thomas E. Tsovilis.)*

The authors are with the High Voltage Laboratory, School of Electrical and Computer Engineering, Aristotle University of Thessaloniki, 541 24 Thessaloniki, Greece (e-mail: gektidis@ece.auth.gr; ialexios@ece.auth.gr; tsovilis@auth.gr).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TIA.2024.3370528.

Digital Object Identifier 10.1109/TIA.2024.3370528

TABLE I
SPD CHARACTERISTICS

SPD	A	B	C
Response time, ns	≤ 100	≤ 100	≤ 100
Voltage protection level, V	≤ 1500	≤ 1500	≤ 1500
Nominal voltage, V	230/400	230/400	230/400
MCOV*, V	255	275	275
Trigger circuit	MOV-based	GDT-based	Resistive
Spark gap technology	Air+particles	Air	Gas mixture
Class per IEC 61643-11	I & II	II	I & II

* Maximum Continuous Operating Voltage

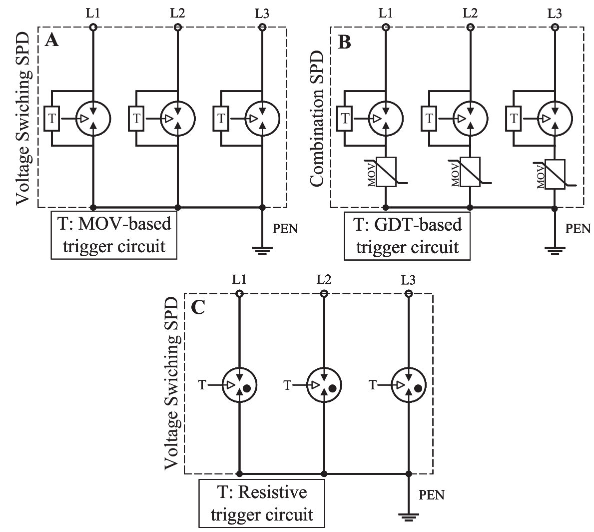

Fig. 1. Schematic diagram of the SPDs under test; Letters A, B, and C are employed to identify the commercially available SPDs presented in Table I.

response time of SPDs, which are associated with the lack of i) test methods for determining the response time of SPDs against fast and very-fast transients [43], [44], [45], ii) a definition of the response time for SPDs in international standards such as the UL 1449 [34], the IEC 61643-11 [46], and the IEEE C62.42.1 [47], iii) an experimental procedure for determining the response time of SPDs under a wide range of surge events that may be exposed to in the field [48], such as slow-front transients, and not only under standard lightning impulses of 6 kV, 1.2/50 μs [46], and iv) analytical studies regarding the statistical nature of the sparkover performance of SPDs with and without triggered circuits; the latter affects the protection level and response time of SPDs, which are both crucial for the protection offered to sensitive equipment.

This work focuses on the transient behavior of SPDs that integrate spark gap technology by employing standard lightning and switching impulse voltages; a preliminary account of that has been given in [49], which is extended in this study to cover a wide range of spark gap technologies and trigger circuit approaches with emphasis given to the statistical analysis of the experimental results regarding the response time and protection level of switching SPDs. The response time of three commercially available spark gap-based DIN-rail SPDs, commonly installed in switchboards of AC three-phase power systems (230/400 V), is investigated. Thus, the statistical nature of the sparkover performance of SPDs is examined for a wide range of surge events [50] that may be exposed to in the field such as fast-front [51] and slow-front transients [52]. The experimental findings are analyzed and discussed, with a clear focus on the sparkover performance of voltage switching SPDs.

II. Devices Under Test

The SPDs under test employ spark gaps between power lines and ground with a substantial follow current extinguish capability that makes them applicable to power grids with prospective short-circuit current of tens of kA; internal components such as MOVs and GDTs are integrated into the triggered circuit and/or in series with spark gaps. The devices under test are produced by different SPD manufacturers and integrate state-of-the-art technologies on spark gap design and trigger mechanisms; the technical ratings and details on the technology employed by the commercially available SPDs are provided in Table I. For all voltage switching and combination-type SPDs under test the response time and let-through voltage are lower than 100 ns and 1500 V, respectively, as declared by manufacturers; a connection type 1 configuration per IEC 61643-12 [6] is adopted, which is applicable to three-phase TN-C systems commonly found in distribution panels in Europe (Fig. 1).

It is noted that triggered spark gap technologies between power lines and ground aim to provide faster response times, lower sparkover voltage, and smaller statistical variation on its sparkover performance [25], [53], [54], [55]; the necessity and effect of trigger circuit on the sparkover performance of spark gap SPDs is illustrated in the Appendix.

III. Experimental Setup and Measurement Procedure

The sparkover performance of the SPDs under test (Table I) was investigated by employing standard lightning (1.2/50 μs) and switching (250/2500 μs) impulse voltages at the High Voltage Laboratory of the Aristotle University of Thessaloniki, Greece.

Before starting experimental activities, ATP-EMTP [56] simulations were performed to ensure the safety of testing staff and equipment that will be used. The schematic diagram of the experimental arrangement is depicted in Fig. 2(a). A single-stage impulse voltage generator (140 kV/245 J), with interchangeable components, was employed to produce double-exponential overvoltage waveforms. The voltage at the SPD terminals was monitored by a voltage probe LeCroy HVP120 (400 MHz), with 0.45 m twisted cables according to [57] to minimize the mutual inductance effects (Fig. 2(b)) as also discussed in [58]. The discharge current was measured by using a Pearson 310 current transformer. Voltage at the output of the generator and the SPD terminals as well as current data were recorded with a Tektronix TDS 3064B digital oscilloscope (600 MHz), following the test procedure of the "Determination of the voltage protection rating (VPR)" per UL 1449 [34] and the "Front of wave sparkover

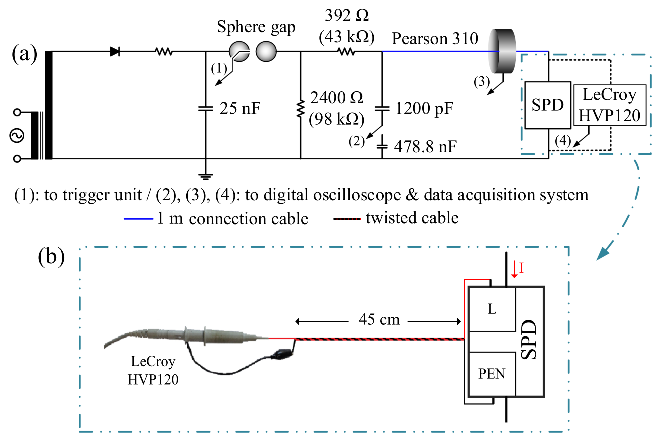

Fig. 2. (a) Schematic diagram of the experimental arrangement employed to determine the response time of SPDs under standard lightning and switching impulse voltages; resistor values in parenthesis were used for the generation of switching impulse voltages. (b) SPD voltage measurement configuration [57].

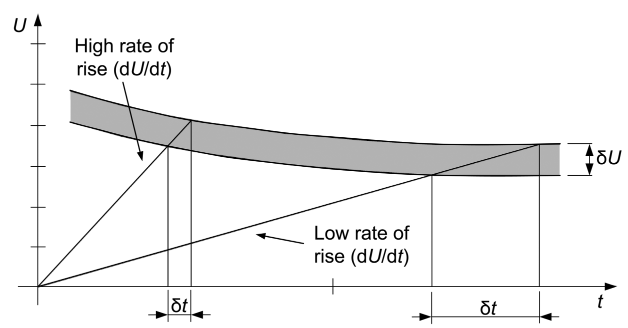

Fig. 3. Sparkover voltage-time curve of a typical spark gap; adapted from [21].

voltage test" per IEC 61643-11 [46], IEC 61643-31 [59], and the forthcoming IEC 61643-01 [35] and IEC 61643-41 [36]. Experimental records were saved to a personal computer through a KUSB-488B adapter enabling data analysis through MATLAB software.

For each SPD, 20 hits of positive and 20 hits of negative polarity were applied at each voltage level so as to obtain a reliable statistical distribution of the protection level and response time of the SPDs based on a sufficient number of measurements. A time interval of ~1 min between impulse voltages was selected as long enough for the SPDs to cool down to ambient temperature per IEC 61643 guidelines; 7 impulse voltage levels from 2 up to 16.5 kV (2, 3.9, 6, 6.4, 8.9, 12.8 and 16.5 kV) were considered. The number of impulse voltage levels and applications is important when considering that the breakdown voltage-time curve of spark gaps is statistical in nature (spread δU, δt in Fig. 3) and highly dependent on the steepness of the applied voltage (Fig. 3); this sparkover performance is inherent in spark gap technology [6].

Based on the recorded voltage and current waveforms, the sparkover voltage and response time of the spark gap-based SPDs were estimated and the associated statistical dispersions

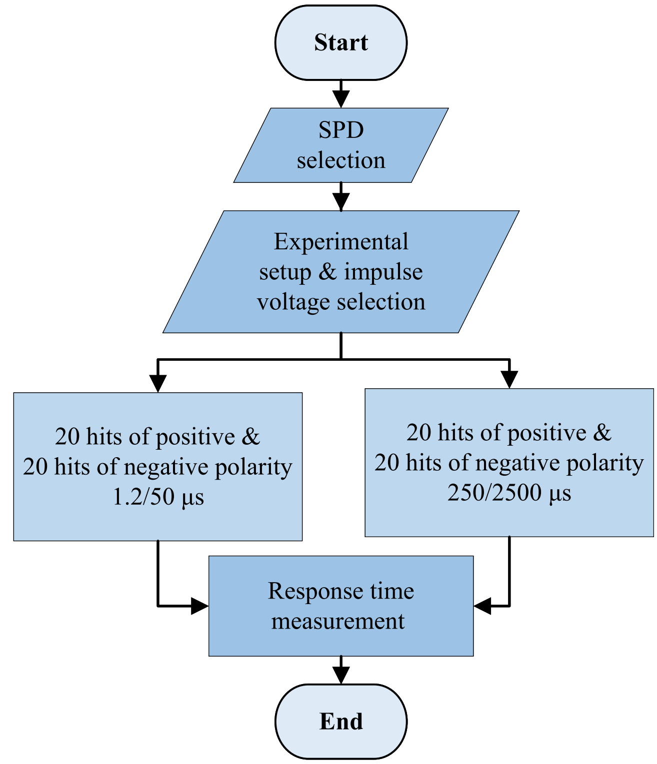

Fig. 4. Flowchart of the adopted experimental procedure.

were documented for each voltage level. The atmospheric conditions, which varied naturally during experiments, were recorded as follows: temperature 27 °C, pressure 760 mmHg, and absolute humidity 19.67 gm^{-3}. A schematic description of the adopted experimental procedure is depicted in the flowchart of Fig. 4.

Aiming to define the response time for switching and combination-type SPDs, to the best of the authors' knowledge for the first time in the international literature, this study proposed three alternative definitions so as i) to ensure impartiality when addressing this issue, ii) to present alternative options, which base their fundamentals on either voltage and/or current measurements, and iii) to present various approaches to international standard committees for evaluating the response time of existing and future SPD technologies. The three definitions of response time (Fig. 5) proposed in this work are:

- Definition 1 (Def. 1): Response time is the time duration from the time instant of the impulse voltage application, t_1, up to the time instant that the sudden drop of the spark gap impedance leads to a considerable current (5% of the peak current value) to flow through the SPD, t_2 (Fig. 5(a)). This definition engages both voltage and current monitoring.
- Definition 2 (Def. 2): Response time is the time duration from the time instant of the impulse voltage application, t_1, up to the time instant, t_2, that the overvoltage is chopped by the SPD. This definition is practically suggesting the response time to be equal to the time to breakdown of the spark gap, as implied by Fig. 5(b).
- Definition 3 (Def. 3): The "clock" starts counting the response time at the time instant that the voltage exceeds a

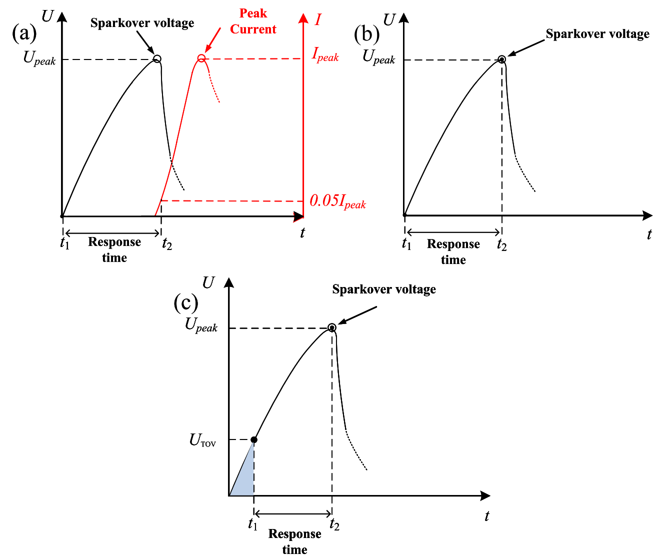

Fig. 5. Definitions of response time proposed in this work. (a) Definition 1, (b) definition 2, and (c) definition 3.

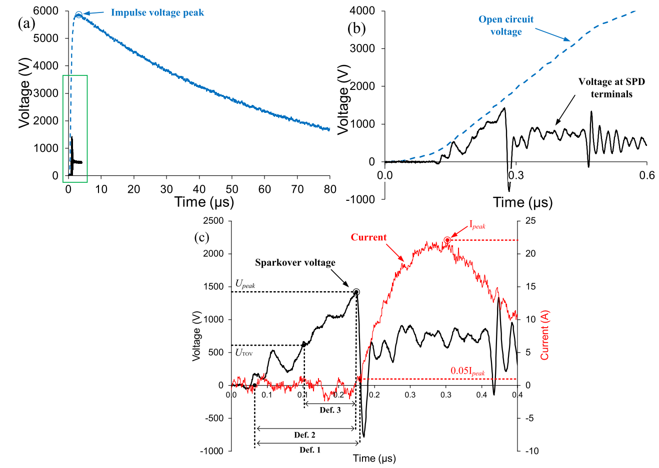

Fig. 6. Lightning impulse voltage tests for 6 kV, 1.2/50 μs. (a) Open circuit voltage and voltage at SPD A terminals (black), (b) zoom in green frame of Fig. 6(a) and, (c) sparkover voltage and response time of SPD A.

threshold value, t_1, up to the time instant of the sparkover voltage, t_2 (Fig. 5(c)); this threshold voltage is considered in this work as the temporary overvoltage peak (U_{TOV}) that may originate due to LV-system faults per Annex B of IEC 61643-11 [46].

The third definition of the response time, which generally yields lower values than definitions 1 and 2, is considered as more representative of the protective effect of the SPD. This is due to the fact that definition 3 demonstrates the "reaction time" of the SPD against transients that attain values threatening the safe operation of protected equipment. It also ignores the duration of the voltage application with values within the temporary overvoltages that voltage switching and combination-type SPDs are not supposed to operate (blue zone in Fig. 5(c)). In addition, estimation of the response time of SPDs based on the proposed definition 3, overcomes measurement challenges associated with oscillations of voltage and current records at the wavefront of voltage and current impulses.

Generally, definition 1 (Fig. 5(a)) yields the longest response times associated with the initiation of the surge current flow through the SPD, definition 2 (Fig. 5(b)) yields shorter response times and coincides with the time to breakdown of the spark gap, and definition 3 (Fig. 5(c)) is associated with the lowest response times reflecting the exposure of the equipment to damaging overvoltages.

IV. Experimental Results

The response time was estimated based on the three proposed definitions (Fig. 5) presented in Section III. The statistical distribution of the response time and sparkover voltage is demonstrated for the total number of hits (20 positive and 20 negative) since no polarity effect has been observed to the spark gap-based SPDs under study, which were not degraded.

A. Lightning Impulse Voltage Tests

Standard lightning impulse voltages up to 16.5 kV have been used to investigate the transient response of SPDs against lightning-related overvoltages. Fig. 6(a) depicts the open circuit standard lightning impulse voltage and the voltage at SPD terminals under 6 kV, 1.2/50 μs and Fig. 6(b) focuses on the initial phase of the transient event (green frame of Fig. 6(a)). Fig. 6(c) shows a typical voltage-current record for SPD A (Fig. 1) and displays the sparkover voltage as well as the response time based on the proposed definitions. The voltage at the SPD A terminals increases up to the sparkover of the SPD ($\sim$1450 V) and then, due to the sudden change of the impedance of the spark gap that is triggered by the MOV-based circuit, a discharge current flows resulting in a residual voltage of $\sim$800 V; the latter residual voltage is associated with the relatively low current flow from the impulse voltage generator. It is noteworthy that the response time of the SPD is estimated approximately 245 ns, 200 ns, and 66 ns per definitions 1, 2, and 3 (Fig. 6(c)); the value of 66 ns per definition 3, that is considered as the most realistic, is in line with the declared response time (<100 ns) of the manufacturer (Table I).

Fig. 7 shows the experimentally derived variation of the response time for all SPDs under examination (A, B, C) as a function of the impulse voltage peak; these results signify the importance of the adopted response time definition (Fig. 5). It is evident that the response time of the SPDs decreases with increasing impulse voltage peak and that the spread of the response time is considerable, especially at lower impulse voltage levels, even though the SPDs under study employ a trigger circuit. It is noted that the larger statistical dispersion on the response time is found for SPD C, which employs a resistive triggered circuit integrated into the switching component; this is denoted by the green solid frame in Fig. 7(c).

It must be noted that definition 3, associated with the largest standard deviation with respect to mean response time $\sigma\%$ among the proposed definitions, is more representative in terms of the estimated SPD response time; it yields results generally

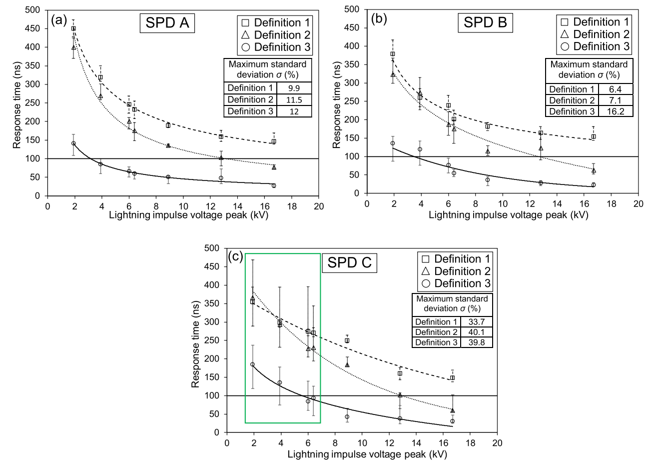

Fig. 7. Response time of SPDs under study versus lightning impulse voltage peak for the 3 proposed definitions. (a) SPD A, (b) SPD B, and (c) SPD C. Squares, triangles, and dots depict the mean response time values (40 hits) for the 3 definitions under study and dashed, dotted, and solid error bars denote the maximum and minimum values for definition 1, 2, and 3, respectively. The horizontal solid line depicts the upper limit of the SPD response time declared by the manufacturers (100 ns).

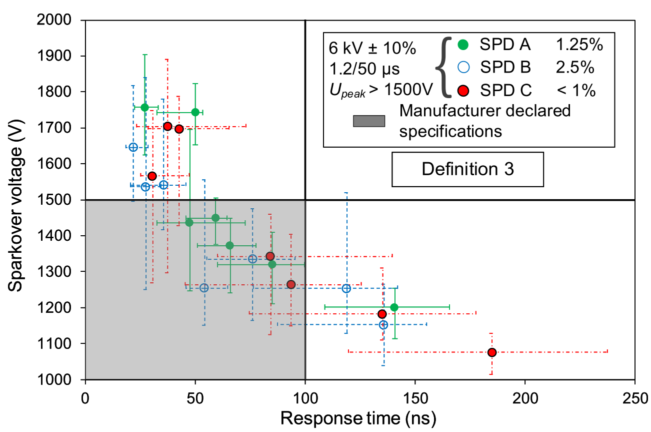

Fig. 8. Sparkover voltage of the SPDs under study versus the response time (definition 3) for lightning impulse voltage tests; circles depict the mean response time (40 hits) together with corresponding error bars denoting the maximum and minimum values of the sparkover voltage and response time. Solid lines depict the upper limit of the let-through voltage (1500 V) and response time (100 ns) declared by the manufacturer; the shaded grey area corresponds to the manufacturer's declared specifications (Table I).

in line with the response time declared by SPD manufacturers (<100 ns) for impulse voltages higher than ∼4000 V (Fig. 6 and Table I). However, for impulse voltages with a peak value lower than ∼3000 V, the response time is definitely larger than the value of 100 ns exceeding the manufacturers response time specifications. Thus, lightning impulse voltage tests with a peak lower than the standard value of 6000 V, 1.2/50 μs, as specified by the IEC 61643-11 [46] and the UL 1449 [34] for sparkover voltage determination, shall be integrated into updated standards to evaluate the response time of SPDs.

Fig. 8 integrates experimental results for all the SPDs under study and definition 3 of the response time. It is obvious that there

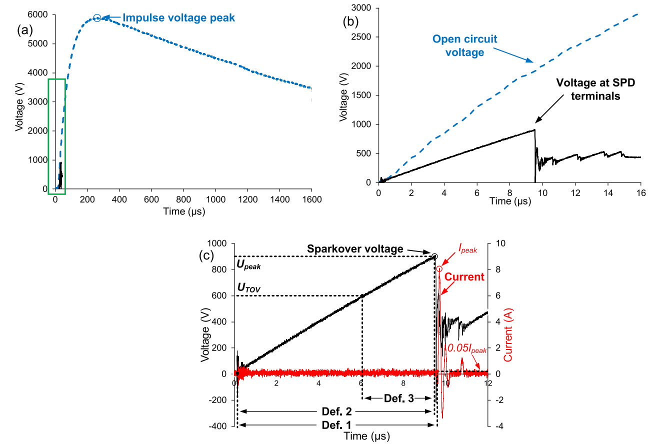

Fig. 9. Switching impulse voltage tests 6 kV, 250/2500 μs. (a) Open circuit voltage and voltage at SPD A terminals (black), (b) zoom in green frame of Fig. 9(a) and, (c) sparkover voltage and response time of SPD A.

are cases where the response time exceeds the declared limit of 100 ns (Table I) for all the SPDs under study! In addition, it is important to note that longer response times, although generally associated with lower sparkover voltages (Fig. 8), may impose a high risk of failure of sensitive equipment. The reason behind this is that the destructive effect on equipment can be attributed not only to the peak overvoltage but also to the duration of the overvoltage that affects the let-through current and specific energy ($\int I^2 t dt$) stressing the protected equipment [60]. It is noteworthy that lightning impulse voltage tests with peak values higher than 6 kV, the latter level is utilized by the IEC61643-11 [46] and the UL 1449 [34], may result in mean sparkover voltages exceeding the protection level of the SPD.

It is important to note that even at 6 kV, 1.2/50 μs (±10%) there is a small probability that SPDs exceed the declared protection level for SPDs A (1 out of 80 hits at 6.0 and 6.6 kV) and B (2 out of 80 hits at 6.0 and 6.6 kV) as indicated by the inset table in Fig. 8; this stresses the need for a stricter quality control of commercially available SPDs that considers the statistical dispersion of the sparkover voltage and the response time.

B. Switching Impulse Voltage Tests

Standard switching impulse voltages up to 16.5 kV have been used to investigate the sparkover performance of SPDs against slow-front transients. Fig. 9(a) depicts the open circuit standard switching impulse voltage and the voltage at SPD terminals under 6 kV, 250/2500 μs; and Fig. 9(b) focuses on the initial phase of the transient event (green frame of Fig. 9(a)). Fig. 9(c) shows a typical voltage and current record for SPD A and presents the sparkover voltage and response time based on the proposed definitions. The voltage at the SPD terminals increases up to the sparkover of the spark gap followed by a sudden drop of the SPD impedance, which is associated with a response time in the microsecond range. These response times are significantly longer than the declared value of 100 ns (Table I) and thus:

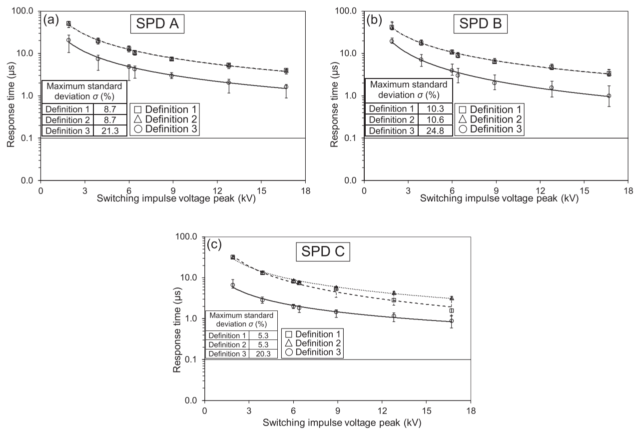

Fig. 10. Response time of SPDs under study versus switching impulse voltage peak for the 3 proposed definitions. (a) SPD A, (b) SPD B, and (c) SPD C. Squares, triangles, and dots depict the mean response time values (40 hits) for the 3 definitions under study and dashed, dotted, and solid error bars denote the maximum and minimum values for definitions 1, 2, and 3, respectively. The horizontal solid line depicts the upper limit of the SPD response time declared by the manufacturers (100 ns); a logarithmic scale is used in y-axis.

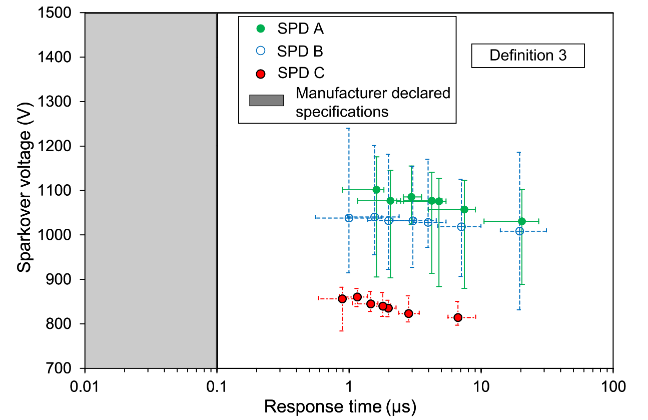

Fig. 11. Sparkover voltage of the SPDs under study versus response time (definition 3) for switching impulse voltage tests; circles depict the mean response time values (40 hits) together with corresponding error bars denoting the maximum and minimum values of the sparkover voltage and response time per case; a logarithmic scale is used in x-axis. The vertical solid line depicts the upper limit of the response time declared by the SPD manufacturers. The shaded grey area corresponds to the manufacturer's declared specifications (Table I).

- call for further investigations on the performance of the trigger circuits of the spark gaps under overvoltages with a low rate of rise and
- question the technical value of the response time declared by manufacturers in case of slow-front transients.

Fig. 10 shows the experimentally derived variation of the response time for all SPDs under study as a function of the switching impulse voltage peak for the proposed response time definitions. Obviously, there is a sharp decrease in the response time of the SPD with increasing switching impulse voltage peak but the response time is always at least an order higher than the declared response time of 100 ns even though all SPDs employ a trigger circuit (Table I).

The response time based on definitions 1 and 2 was found almost equivalent for all switching impulse voltage peaks; this is due to the fact that the time to breakdown of the spark gap is significantly larger than the time difference between the sparkover voltage and the 5% of current peak flowing through the SPD, as can been seen from Fig. 9(c). It is noted that definition 3 yields the lowest response time and is associated with the largest standard deviation $\sigma\%$ among the proposed definitions, as was also found for lightning impulse voltages. Fig. 11 integrates experimental results for all the SPDs under study (A, B, C) for the proposed definition 3.

It must be noted that these long response times are associated with the relatively low sparkover voltages that attain values between ∼800–1300 V; despite being certainly below the declared SPD protection level of 1500 V, these sparkover voltages may still be harmful to sensitive equipment in case of prolonged duration.

These experimental findings on long response times (Figs. 10 and 11), which are well beyond the response time declared by SPD manufacturers, stress the need for a new category of the response time of SPDs against slow-front transients; switching transients may occur in power systems [52] and the response time of the SPDs against slowly rising overvoltages can be a critical protection parameter. For instance, if a voltage level of 6 kV, 250/2500 μs is adopted, a response time against slow-front transients for the SPDs under study based on definition 3 would be ∼5 μs for SPD A, ∼4 μs for SPD B, and ∼2 μs for SPD C (Fig. 10). It should be mentioned that results of this work regarding the response time are not only related to the spark gap technology but can also be directly associated with other voltage switching and combination-type SPDs [60], [61], [62] as well as gapped surge arresters [63], [64], [65].

V. Discussion

As presented in the experimental analysis of the previous section, the response time of SPDs of different technologies currently employed in the surge protection industry may exceed the threshold of 100 ns declared by manufacturers. Considering the fact that international standards such as IEC 61643 [36], [46], [49] and UL 1449 [34] related to SPD specifications do not incorporate a test method for its determination, this study reveals i) an important omission in related standards development [35], [47] as well as IEEE surge protection guides [1], [7], and ii) a research gap in SPD transient performance with emphasis to the response time that needs to be rigorously explored by industry and academia.

Results of this work and the associated analysis may contribute to: i) stress the importance of defining the response time of SPDs in forthcoming international standards, ii) emphasize the need for a new response time category for SPDs against slow-front transients, iii) introduce a new, realistic definition for SPD's response time, along with a suggested experimental setup for its measurement; this will form the basis for the evaluation of existing and future SPD technologies, and iv) reveal the potential risks of SPD's response time and sparkover voltage exceeding the declared protection levels.

This work marks the initial phase of an experimental investigation aiming to evaluate the transient behavior of switching and combination-type SPDs; findings hold significance for international standard committees, manufacturers, and insulation coordination engineers. Nevertheless, in order to make a thorough investigation, it's essential to acknowledge the limitations of this study, that also form the topics of future work: i) increase the number of the devices under test to include more SPD technologies [66], ii) analyze the transient performance of SPDs under a wide range (very-fast to slow) of impulse voltages and currents as well as a combination of them [48], [51], [52], iii) study of the effect of degradation [67], temperature [37], pressure [68], and absolute humidity [69] on the response time, particularly for spark gaps employing non-encapsulated air as a dielectric, iv) analyze the effect of the type of load on the response time of SPDs [70], and v) estimate the let-through energy ($\int I^2 tdt$) stressing the protected equipment based on different triggered spark gap and GDTs [60].

VI. Conclusion

This work proposes a novel definition of the response time, which considers the "reaction time" of spark gaps. Analysis of the experimental results on the sparkover performance of state-of-the-art SPDs employing different spark gap technologies has shown that the response time:

- varies considerably with impulse voltage peak and takes values beyond the threshold of 100 ns declared by SPD manufacturers, especially for fast-front overvoltages with a peak value lower than ~3 kV,
- is at least an order of magnitude higher for switching than lightning impulse voltages; SPDs exhibit a response time in the μs range for slow-front overvoltages, which is significantly longer than the declared response time of 100 ns,
- is statistical in nature, and the associated spread is significant for all trigger circuit technologies under investigation; the standard deviation of the response time of SPDs takes values up to ~40%.

These findings stress the need for the introduction of a definition of the response time of SPDs in forthcoming international standards. Such an update can be an innovation driver [71] and tool for evaluating the efficiency of existing and future technologies of SPDs.

Appendix

Fig. 12 shows the sparkover performance of the spark gap-based SPD A (Table I) under 6 kV/ 3 kA, generated with the aid of a Hilo PG12-804 combination wave generator per UL 1449 [34]. It is obvious that both the response time and the sparkover voltage of the SPD increase significantly without the integration of the trigger circuit into the spark gap; these results are indicative of the necessity, value, and positive effect of the trigger circuit on the protection efficiency of SPDs.

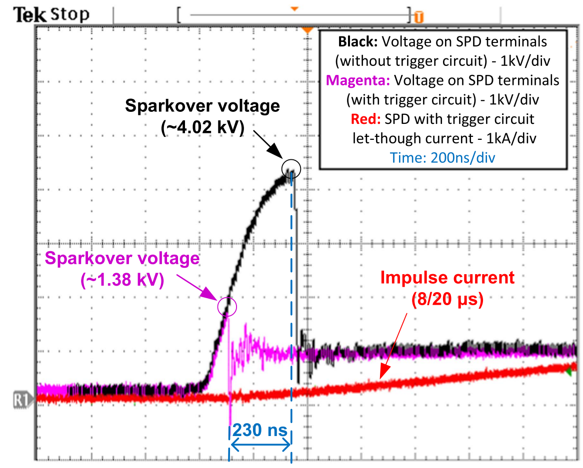

Fig. 12. Comparison of the sparkover performance of SPD A with and without integration of the trigger circuit under 6 kV, 1.2/50 μs / 3 kA, 8/20 μs per UL 1449 [34].

Acknowledgment

Prof. Thomas E. Tsovilis dedicates this paper to the memory of Mr. Costas Apostolidis, founder of Raycap Corporation, in recognition of his significant contributions to his professional and personal growth. He would also like to thank Mr. Thomas Kohushölter, Head of VDE Testing and Certification Institute in Berlin, for their fruitful discussions on the response time of SPDs.

References

[1] A. Rousseau, *Surge Protection for Low Voltage Systems* (Energy Engineering Series), vol. 182, London, U.K.: IET, 2021.
[2] *IEEE Guide for Surge Protectors and Surge Protective Circuits Used in Information and Communication Technology Circuits (ICT), Including Smart Grid–Part 1 Applications*, IEEE Standard C62.43.1, Institute of Electrical and Electronics Engineers, Piscataway, NJ, USA, 2020.
[3] *Standard for the Installation of Lightning Protection Systems*, NFPA Standard 780, National Fire Protection Association, Boston, MA, USA, 2023.
[4] M. Bruch et al., "Power blackout risks: Risk management options," in *CRO Forum Emerging Risk Initiative*, 2011.
[5] E. Davis, N. Kooiman, and K. Viswanathan, "Data assessment for electrical surge protection devices," in *The Fire Protection Research Foundation: Phase 1, Final Report*, 2014.
[6] *Low-Voltage Surge Protective Devices- Part 12: Surge Protective Devices Connected to Low-Voltage Power Systems – Selection and Application Principles*, IEC Standard 61643-12, International Electrotechnical Commission, Geneva, Switzerland, 2020.
[7] IEEE Guide for Surge Protection of Electric Vehicle Infrastructure, C62.230, 2022.
[8] German Insurance Association, Blitzbilanz 2021: Anzahl und Höhe der Schäden steigen, Link Last Accessed Mar. 2024. [Online]. Available: https://www.gdv.de/gdv/medien/medieninformationen/blitzbilanz-2021-anzahl-und-hoehe-der-schaeden-steigen--85642
[9] VAISALA, Total Lightning Statistics, 2021 Annual Lightning Report, Link Last Accessed Mar. 2024. [Online]. Available: https://www.vaisala.com/sites/default/files/documents/WEA-MET-2021-Annual-Lightning-Report-B212465EN-A.pdf
[10] M. M. F. Saba, D. R. R. da Silva, J. G. Pantuso, and C. L. da Silva, "Close view of the lightning attachment process unveils the streamer zone fine structure," *Geophysical Res. Lett.*, vol. 49, no. 24, Dec. 2022, Art. no. e2022GL101482.
[11] F. D. Martzloff, "Matching surge protective devices to their environment," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 1, pp. 99–106, Jan. 1985.

[12] K.-C. Lai, W.-J. Lee, and W. V. Jackson, "Testing and selecting surge suppressors for low-voltage AC circuits," *IEEE Trans. Ind. Appl.*., vol. 26, no. 6, pp. 976–982, Nov./Dec. 1990.
[13] K. Samaras, C. Sandberg, C. J. Salmas, and A. Koulaxouzidis, "Electrical surge-protection devices for industrial facilities—A tutorial review," *IEEE Trans. Ind. Appl.*., vol. 43, no. 1, pp. 150–161, Jan./Feb. 2007.
[14] D. Paul and V. Haddadian, "Transient overvoltage protection of shore-to-ship power supply system," *IEEE Trans. Ind. Appl.*, vol. 47, no. 3, pp. 1193–1200, May/Jun. 2011.
[15] E. T. Staikos, G. D. Peppas, and T. E. Tsovilis, "Wide frequnecy response of varistors and coordination with transient voltage suppression diodes," *IEEE Trans. Power Del.*, vol. 38, no. 1, pp. 453–462, Feb. 2023.
[16] P. B. Vilar, G. R. S. Lira, E. G. Costa, V. S. Brito, and M. J. d. A. Maia, "Development of a model for calculation of energy absorbed by a ZnO surge arrester during transients," *IEEE Trans. Power Del.*, vol. 37, no. 1, pp. 136–145, Feb. 2022.
[17] P. Kerur, "PCB sparks gaps for surge voltages and EMC/EMI protection in future electric vehicle charging," *GIS Sci. J.*, vol. 10, no. 3, pp. 1599–1611, Mar. 2023.
[18] S. Chen et al., "Surge protective device failure caused by triggered lightning continuing current and M component," *Electric Power Syst. Res.*, vol. 218, May 2023, Art. no. 109225.
[19] A. Y. Hadjicostas, E. T. Staikos, G. D. Peppas, and T. E. Tsovilis, "A simplified transient model of surge protective devices employing varistors," *Electr. Pow. Syst. Res.*, vol. 224, Nov. 2023, Art. no. 109601.
[20] N. Dong, Y.-Z. Xie, Y. Wu, Z. Li, and F. G. Canavero, "An equation-based dynamic nonlinear model of metal-oxide arrester and its spice implementation," *IEEE Trans. Circuits Syst. II: Exp. Briefs*, vol. 70, no. 8, pp. 2919–2923, Aug. 2023.
[21] S. Yasui, T. Kano, N. Triruttanapiruk, and T. Tsuchida, "Lightning surge overvoltage protection for low-voltage equipment placed outdoors in TT system," *IEEE Trans. Electromagn. Compat.*, vol. 65, no. 3, pp. 831–838, Jun. 2023.
[22] A. Ehrhardt, S. Schreiter, and S. Beier, "Spark gap having plurality of individual spark gaps connected in series and present in a stacked arrangement," U.S. Patent 9,184,569 B2, Nov. 10, 2015.
[23] J. Cerny, T. Meyer, and R. Durth, "Surge protector," U.S. Patent 8,958,194 B2, Feb. 17, 2015.
[24] Lightning Protection Guide, 3rd Updated ed., DEHN, 2014.
[25] R. Rozman, "Gas discharge tube assemblies," U.S. Patent 10,685,805 B2, Jun. 16, 2020.
[26] V. Cooray, "Internal lightning protection system," in *Lightning Protection* (IET Power and Energy Series), vol. 58, V. Cooray, Ed. London, U.K.: IET, 2010.
[27] L. Huttner, L. Jurcacko, F. Valent, A. Ehrhardt, S. Schreiter, and M. Rock, "Basic problems and solution of the encapsulation of a low-voltage spark gap with arc splitter chamber," *J. Electric Eng.*, vol. 63, no. 2, pp. 103–108, Apr. 2012.
[28] G. Finis, M. Wetter, and T. Meyer, "New spark-gap technology with efficient line-follow current suppression for the protection of powerful LV distribution systems," in *Proc. IEEE 33rd Int. Conf. Lightning Protection*, 2016, pp. 1–7.
[29] G. V. Podporkin, M. Wetter, and H. Heckler, "Surge-protective devices," in *Lightning Interaction with Power Systems - Volume 1: Fundamentals and Modelling*, A. Piantini, Ed. Stevenage, U.K.: Inst. Eng. Technol., Jan. 2020, pp. 287–343.
[30] S. Ait-Amar, J. B. Ducourneau, G. Serrie, and M. Abplanalp, "Arc extinguishing method of SPD type 1," *IEEE Trans. Dielectrics Elect. Insul.*, vol. 16, no. 3, pp. 711–717, Jun. 2009.
[31] T. H. Kopp, M. Kurrat, and B. Schottel, "Circuit behavior during operation duty test applying spark gap technology based arresters," in *Proc. IEEE 32nd Int. Conf. Lightning Protection*, 2014, pp. 1365–1369.
[32] S. Yanagawa, Y. Miyama, T. Sawamura, A. Omi, and K. Yamamoto, "Lightning surge response characteristics of SPDs used for protecting an electronic apparatus," in *Proc. IEEE Asia-Pacific Int. Symp. Electromagn. Compat.*, 2010, pp. 1267–1270.
[33] Y. Naito, S. Yanagawa, T. Kawabata, and K. Yamamoto, "Response characteristics of diode gas discharge tubes," in *Proc. IEEE 29th Int. Conf. Lightning Protection*, 2012, pp. 1–4.
[34] *Standard for Safety, Surge Protective Devices*, Standard UL 1449, 2021.
[35] *Low-Voltage Surge Protective Devices - Part 01: general Requirements and Test Methods*, IEC Standard 61643-01 ED1, International Electrotechnical Commission, Geneva, Switzerland, 2024.
[36] *Low-Voltage Surge Protective Devices - Part 41: Surge Protective Devices Connected to DC Low-Voltage Power Systems – Requirements and Test Methods*, IEC Standard 61643-41 ED1, International Electrotechnical Commission, Geneva, Switzerland, 2024.
[37] R. W. Hotchkiss, "Response time and surge protective devices: Characterization in real time," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, 2011, pp. 1–6.
[38] H. Tang, V. Scuka, M. Cergolj, and M. Trontelj, "Transient control characteristics of low voltage varistors," in *Proc. 1995 Int. Conf. Contr. Autom. Elect. Pow. Syst.: VAES-95*, Ljubljana, Slovenia, 1995, pp. 1–10.
[39] *Standard for Test Methods and Performance Values for Metal-Oxide Varistor Surge Protective Components*, IEEE Standard C62.33, 2018.
[40] Surge Protective Device Response Time, SPDs and UL 1449 3rd Edition, Schneider Electric, Link Last Accessed Mar. 2024. [Online]. Available: https://media.distributordatasolutions.com/schneider2prod/2018q2/8949268504658cbb7a7285151f455d5de7e7209e
[41] Application notes: response time ratings, Power quality Surge Protective Devices (SPD), General Electric, Link Last Accessed Mar. 2024. [Online]. Available: https://library.industrialsolutions.abb.com/publibrary/checkout/DET-733?TNR=Application%20and%20Technical%7CDET-733%7CPDF&filename=DET-733%20-%20Response%20Time%20Ratings%20for%20SPDs.pdf
[42] Metal Oxide Varistor (MOV) versus Silicon Avalanche Suppressor Diode (SASD) Designs Discussion, Transtector Surges and Suppressor Technologies: Comparing Apples to Oranges, Transtector, Link Last Accessed Mar. 2024. [Online]. Available: https://www.polyphaser.com/News/DownloadFile?downloadGuid=596911d3-f38a-42eb-a685-b0de5cc63e24
[43] Y.-Z. Xie, T. Liang, and K.-J. Li, "Quantitative determination of response time and time-varying characteristics of surge protective devices," *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 5, pp. 982–988, Oct. 2015.
[44] Y.-Y. Wu, Y.-Z. Xie, H. Cao, N. Dong, and Y.-P. Ge, "Test methods for performance of protective devices excited by conducted transient electromagnetic disturbance," in *Proc. IEEE 7th Glob. Electromagn. Compat. Conf.*, 2023, pp. 19–20.
[45] Y. Zhou, Y.-Z. Xie, D.-Z. Zhang, N. Dong, Y.-H. Chen, and Y. Jing, "Response of 10-kV metal-oxide surge arresters excited by nanosecond-level transient electromagnetic disturbances," *IEEE Trans. Electromagn. Compat.*, vol. 63, no. 2, pp. 614–621, Apr. 2021.
[46] *Low-Voltage Surge Protective Devices - Part 11: Surge Protective Devices Connected to Low-Voltage Power Systems – Requirements and Test Methods*, IEC Standard 61643-11, International Electrotechnical Commission, Geneva, Switzerland, 2011.
[47] *Guide for the Application of Surge-Protective Components in Surge Protective Devices and Equipment Ports - Part 1: gas Discharge Tubes (GDTs)*, IEEE Standard C62.42.1, 2016.
[48] C. Bean, H. Gupta, and V. Kniaziev, "The testing methods for surge protective devices," in *Proc. IEEE 30th Int. Conf. Lightning Protection*, 2010, pp. 1–5.
[49] K. M. Gektidis, A. I. Ioannidis, and T. E. Tsovilis, "Response time of surge protective devices employing spar gap technology," in *Proc. IEEE Ind. Appl. Soc. Annu. Meeting*, 2022, pp. 1–9.
[50] D. Paul and S. Venugopalan, "Power distribution system equipment overvoltage protection," in *Proc. IEEE Ind. Appl. Conf. 28th IAS Annu. Meeting*, 1993, pp. 1560–1569.
[51] Y. Zhang, H. Chen, Y. Du, Z. Li, and Y. Wu, "Lightning transient analysis of main and submain circuits in commercial buildings using PEEC method," *IEEE Trans. Ind. Appl.*, vol. 56, no. 1, pp. 106–116, Jan./Feb. 2020.
[52] M. Berger, J. P. M. Grave, C. Lavertu, I. Kocar, J. Mahseredjian, and D. Ferrara, "Modeling, simulation, and testing of switching surge transients in rapid transit vehicles DC Power Systems," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 822–831, Jan./Feb. 2018.
[53] A. Ehrhardt, M. Waffler, and S. Hierl, "Encapsulated, pressure-proof, non-hermetically sealed, rotationally symetrical high-power spark gap," European Patent office, EP1966860B1, Dec. 3, 2007.
[54] R. Brocke, "Arrangement for overload protection for overvoltage protection equipment," European Patent office, EP3446379B1, Apr. 4, 2017.
[55] K. Bernhard, L. Christian, H. Sebastian, E. Roland, K. Juliane, and D. Richard, "Surge arrester spark gap assembly and method of operating one Surge Arrester spark gap arrangement," *Deutsches Patent. und Markenamt*, DE 10 2021 208 076 A1, Feb. 2, 2023.
[56] H. K. Høidalen, L. Prikler, and F. Penaloza, *ATPDraw Version 7.3 for Windows Users' Manual*. NTNU Norway, 2021.
[57] OSM/IN 288 for EN 61643 series + EN 50539 series, "General instruction for residual voltage measurements," Decided (meeting 28), 2018.
[58] K. Schon, "High impulse currents," in *High Voltage Measurement Techniques*, K. Schon, Ed. Cham, Switzerland: Springer Nature, 2019.

[59] *Low-Voltage Surge Protective Devices - Part 31: requirements and Test Methods for SPDs for Photovoltaic Installations*, IEC Standard 61643-31, International Electrotechnical Commission, Geneva, Switzerland, 2018.

[60] T. E. Tsovilis, “Critical insight into performance requirements and test methods for surge protective devices connected to low-voltage power systems,” *IEEE Trans. Power Del.*, vol. 36, no. 5, pp. 3055–3064, Oct. 2021.

[61] Y. Gannac, G. Leduc, C.-D. Pham, and V. Crevenat, “8/20 and 10/350 surges behaviour of a gas discharge tube according to gas pressure,” *Electric Power Syst. Res.*, vol. 197, Aug. 2021, Art. no. 107302.

[62] T. E. Tsovilis, A. Y. Hadjicostas, E. T. Staikos, and G. D. Peppas, “An experimental methodology for modeling surge protective devices: An application to DC SPDs for electric vehicle charging stations,” *IEEE Trans. Indus. Appl.*, vol. 60, no. 1, pp. 1645–1655, Jan.-Feb. 2024.

[63] G. V. Podporkin, E. Y. Enkin, E. S. Kalakutsky, V. E. Pilshikov, and A. D. Sivaev, “Overhead lines lightning protection by multi-chamber arresters and insulator-arresters,” *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 214–221, Jan. 2011.

[64] *Surge Arresters - Part 8: metal-Oxide Surge Arresters with External Series Gap (Egla) for Overhead Transmission and Distribution Lines of a.c. Systems Above 1 kV*, IEC Standard 60099-8, International Electrotechnical Commission, Geneva, Switzerland, 2017.

[65] Z. G. Datsios, P. N. Mikropoulos, T. E. Tsovilis, E. Thalassinakis, and G. Pagonis, “Investigation of line surge arresters application to the 150 kV system of Rhodes,” *Electric Power Syst. Res.*, vol. 213, Dec. 2022, Art. no. 108763.

[66] M. An, H. Lu, W. Zhao, C. Zheng, Y. Wang, and Y. Hu, “An experimental study on novel gas discharge tubes with graphene as electron emission material,” *IEEE Trans. Electron Devices*, vol. 70, no. 4, pp. 1942–1949, Apr. 2023.

[67] L. Cheng, N. Xiang, K. Bian, Z. Xu, L. Wang, and J. Yang, “The effects of long-term operation on the insulation resistance of gas discharge tube,” in *Proc. IEEE 7th Int. Conf. High Voltage Eng. Appl.*, 2020, pp. 1–4.

[68] D. D. T.Allibone, “Influence of humidity on the breakdown of sphere and rod gaps under impulse voltages of short and long wavefronts,” *IEE Proc.*, vol. 119, no. 5, pp. 1417–1422, Sep. 1972.

[69] P. Mikropoulos and C. Stassinopoulos, “Impulse breakdown of short rod–plane gaps and the influence of humidity,” *IEE Proc.: Sci., Meas. Technol.*, vol. 108, no. 40, pp. 141–146, Jul. 1998.

[70] J. He, Z. Yuan, S. Wang, J. Hu, S. Chen, and R. Zeng, “Effective protection distances of low-voltage SPD with different voltage protection levels,” *IEEE Trans. Power Del.*, vol. 25, no. 1, pp. 187–195, Jan. 2010.

[71] G. Zissis, “Codes and standards as innovation drivers [President’s Message],” *IEEE Ind. Appl. Mag.*, vol. 26, no. 1, pp. 4–66, Jan./Feb. 2020.

Konstantinos M. Gektidis (Student Member) was born in Thessaloniki, Greece, in 1998. He received the M.Eng. degree in electrical and computer engineering from the Aristotle University of Thessaloniki (AUTh), Greece, in 2021. He is currently pursuing the Ph.D. degree in the High Voltage Laboratory, AUTh. His research is focused on surge protection of sensitive electronic equipment to achieve more safe, reliable, and economical electrical installations. Emphasis is given to the development of novel surge protection schemes for targeted surge protection.

Alexios I. Ioannidis (Member, IEEE) was born in Ptolemaida, Greece in 1993. He received the M.Eng. and Ph.D. degrees in electrical and computer engineering from the Aristotle University of Thessaloniki, Thessaloniki, Greece, in 2017 and 2023, respectively. His research interests include the fields of high-voltage engineering, lightning protection and lightning performance of transmission lines, electromagnetic transient simulations, and computational electromagnetics. In 2022, he received the Diploma for Young Scientists at the International Conference on Lightning Protection. He was one of the recipients of the IEEE Dielectrics and Electrical Insulation Society Graduate Student Fellowship in 2020.

Thomas E. Tsovilis (Senior Member) was born in Piraeus, Greece, in 1983. He received the M.Eng. and Ph.D. degrees in electrical and computer engineering from the Aristotle University of Thessaloniki (AUTh), Thessaloniki, Greece, in 2005 and 2010, respectively. He held various managerial positions with the R&D Department of Raycap Corporation leading innovation in surge protective devices. He was the Director of the High Current Labs of Raycap, Drama, Greece, from 2012 to 2015 and in Ljubljana, Slovenia, from 2016 to 2018. In 2018, he joined AUTh, where he is currently an Associate Professor. He is the Inventor of eight granted U.S. patents on surge protective devices and testing techniques. He has authored more than 100 scientific papers in his research areas which include the broad area of high voltage engineering with emphasis given to electrical discharges, lightning and surge protection, and insulation coordination for power systems. He is the recipient of the Myron Zucker Student-Faculty Grant Award from the IEEE Industry Applications Society in 2019 and 2022.