Voltage-time Characteristics of Air Gaps and Insulation Coordination - Survey of 100 Years Research -

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Abstract— With the first application of HV-power lines at the early 20th century the protection of electric components against lightning strokes became a crucial problem. Albeit the overhead insulators were designed to withstand high ac-voltages above the operating level, they failed under stress of high impulse voltages with unknown shape. The need to generate short-time HV-impulses was solved in the 1920th by the invention of the „Marx-Generator“. At least it was observed that the flashover voltage of an insulator is higher for shorter than for longer pulses. During the following decades HV-power networks expanded worldwide rapidly and with it grew the need of HV-impulse tests in laboratories. Progress in short time measurement techniques allowed to reproduce impulses of defined shape and amplitude. In order to establish compatibility of discharge tests in the Megavolt-range, standard pulse shapes were internationally agreed upon. Of special interest for an effective coordination of various insulation structures became data of spark-over values of air gaps with very short time lags.

However, a great number of measurements did not lead to satisfying results for non-standard test-voltages. Attempts to derive formulae for good results were neither easy to use nor reliable. Finally, an approach starting from the first principle of discharge in an air gap assuming the speed of leader growth being proportional to the instant voltage above the withstand value led to a simple and generally applicable criterion.

Further development of physical models for the leader propagation process leads to self-reliant calculation methods, which are simply coupled to average field calculations.

Keywords: Insulation coordination; Impulse-voltage ratio; Volt-time area; Integration method; Equal-area criterion; Leader propagation method

I. INTRODUCTION

J.C. Maxwells „Treatise on Electricity and Magnetism“ opened the theoretical door to the industrial application of Electrical Power in 1873. As an example: It took only few decades to bridge the gap from theory to the development of power stations including a.c. power transmission lines. Milestones were the first HV–overhead lines in USA and Germany already before the turn of the century. The lack of full theoretical understanding and missing equipment for measurements and generation of impulse voltages did not prevent ingenious engineers from experimental applications.

Even careful physics based design and serious dimensioning could not avoid any failures in expensive installations and this is true for the protection of HV-overhead lines against lightning strokes. Only well planned experiments with typical insulators could improve the missing knowledge. Therefore the voltage-time characteristics of airgaps are until today not only of interest for insulation coordination but also for further basic research on breakdown in gases.

II. IMPULSE-VOLTAGE RATIO ACCORDING TO MARX¹ 1924

One important requirement for the operation of transmission lines was the development of a reliable insulation. The successfully developed ceramic insulators fulfilled the given requirements under real environmental conditions.

The once market-leading company for ceramic insulators HESCHO was testing lightning impulse voltages on ceramic insulators in their test field. The laboratory coordination of the test field was given to Erwin Marx who wrote his doctor thesis at the Technische Hochschule Dresden. He investigated the behavior of the ceramic insulators comprehensively and well-considered. The results were published in June 1925 [1].

He obviously had studied the famous book “Dielectric Phenomena in High Voltage Engineering” by F.W. Peek, published 1915 when Electrical Engineering, was still in need of experimental results. As far as the reliability of HV ceramic insulators is concerned, Peek wrote: “At the present time a great deal is said of the effects of “high frequency” on insulation without differentiating between continuous sine wave, high frequency oscillations and steep front impulses. This has caused considerable confusion”[2].

¹ Erwin Marx, born 1893 in Mautitz near Riesa in Saxony, studies at Technische Hochschule Dresden, 1925 full professor at the Technische Hochschule in Braunschweig
The breakdown voltage of multiple cap insulators for impulse voltages was found to be higher than the maximum of alternating voltages as shown in Figure 1. Following a proposal of F.W. Peek (“who has done much work on this field”), Marx named the quotient “impulse ratio”. A further result was that steep rising and fast decreasing impulses showed a much higher impulse ratio [1].

Firstly a circuit had to be developed in order to generate test voltages with amplitudes higher than the common alternating voltage. Secondly the voltage curve characteristics had to be chosen with a high comparability to the occurring stress during operation. Concepts for this were already known through estimations of the lightning currents and calculations on the background of current circuit characteristics, but no direct measurements of this behavior. The first measurements were published in 1925 using a cathode ray oscillograph in order to make traveling waves visible [3].

In the 20’s of the last century, there was only little knowledge about the front time of lightning impulse voltages available [4]. But the researchers were aware about the great importance of the travelling wave steepness for insulation-coordination. Front times in the range of 0.1 µs were assumed.

Figure 2 shows several impulse voltage wave forms, derived by calculations from the generation circuit given in the picture. As the Spark gap $F_1$ is designed with sphere-geometry, the response time can be assumed as negligibly small and in the event of a spark a square impulse “c” is generated with double the voltage compared to the feeding direct voltage.

The breakdown of pin electrodes (NF) occurs after a long discharge propagation time. A high ratio between the flashover voltage and the a.c. breakdown voltage was concluded for fast rising lightning impulses.

From today’s understanding the curves a and b are full impulse voltages, c can be assumed to be equivalent to the static d.c. breakdown voltage. The breakdown process takes place while the applied voltage is higher than the d.c. breakdown voltage. As a result of several tests with different lightning impulses the typical Voltage-time Characteristics are received.

From the circuit diagram for the generation of high impulse voltages it can be deduced that Marx invented the worldwide known, patented in 1923, multiplier circuit at that time. The title of one presentation held by Erwin Marx during this time was named: “The direct current - impulse voltage test of insulation”. The title was inspired by the fact that every circuit is based on capacitors and that the impulse voltage is triggered through spark gaps.

### III. AREAS OF IMPULSE-VOLTAGE CURVES ACC. TO HAGENGUTH² 1941

After the First World War high voltage technology became more and more important due to the fact that the operation voltage was raised. After the first 220 kV transmissions line in Germany the USA followed in 1937 with the first three phase transmission at 345 kV. One important company for the development of the necessary components was General Electric Co in Pittsfield, Ma. Manufactured systems were: transformers, voltage regulators, cut-outs, current limiting reactors, lightning arrestors, capacitors and much more. In 1928 General Electric employed 7000 staff members in different factories.

One important challenge for the operational safety of the distribution transformers was the danger of traveling waves

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² J.H. Hagenguth, born in 1901 in Greifswald, Germany, studied at Technische Hochschule München, 1926 General Electric Co in Pittsfield, Ma
caused by lightning strikes in transmission lines. Originating from a first high-voltage laboratory in 1914 in Pittsfield a center of the lightning research was developed. Here L.V. Bewley works as a researcher starting in 1928. He was a world renowned expert in surge phenomena and lightning-related disturbances on high voltage transmission lines. Under his supervision the first measurements of overvoltages through natural lightning were performed [5].

In order to rate the insulation capabilities during an impulse voltage it became necessary for an effective insulation coordination to investigate the time dependent curve of the electrical resilience of grid components. To compare the many measurements and results of the impulse voltage tests in different countries a standard for the lightning impulse voltage became necessary in the 1930th.

After the successful measurement of traveling waves, lightning impulses with a rise time of 1 µs and a time to half value of approximately 50 µs where standardized (e.g. in Germany designated as 1/50 in accordance with VDE 1939). The generators are mostly based on direct current loaded capacitors for generating aperiodic impulses. With higher test voltages the influence of unpreventable higher inducivities leads to superposed oscillations. This oscillation makes the ensuring of tolerances much more difficult.

In 1937 the paper from J.H. Hagenguth with the title “Short-Time-Spark-Over of Gaps” was published. With this as a foundation he investigated the meaning of impulse voltage parameters (volt-time areas) for the usage in the insulation coordination [6] in the following years. He presented his results of his several year-long experimental research programs in a comprehensive publication in 1941 [7] in which he named the entirety of voltage-time curves of certain gaps “volt-time area”. The aim of this research program was to investigate impulse voltage characteristics of different electrode configurations and impulse curves up to the MV-range.

For that he wrote as an example: „The problem of insulation coordination on the basis of breakdown has become of great concern to the operating engineer. Many papers have been written on the large problem. It will be left to the physicist to translate the following data into electrons, ions and term of photo-ionization. This paper will attempt to present the data in terms which the engineer interested in coordination. “

As an important result he wrote: “Impulse spark-over voltages of electrode arrangements with non-uniform field - such as insulators, bushings, rod gaps - cannot be represented with sufficient accuracy by (single) volt-time curves, but must be represented by volt-time areas,” compiled of several volt-time curves with various time parameters. As an example the breakdown behavior of a negative rod spark gap is presented in Figure 3. It is not fundamentally different compared to the ceramic suspension insulators.

This is also visible in Figure 4 which presents qualitative results of a comprehensive research project on air gaps used in high voltage grids.
time is reflected by his statement: "The great differences in voltage at any given time to breakdown are not due to erratic nature of breakdown, but due to differences in the shape of the applied impulse wave before breakdown occurs" [7].

IV. INTEGRATION METHOD ACC. TO JONES’ 1954

Through the buildup of high voltage supply grids the insulation coordination obtained increasing attention in the US and in many other countries. This led to extensive recordings of volt-time curves for different impulse shapes of technical relevant insulation configurations up to the range of MV in many laboratories. The volt-time characteristics of Hagenguth shown in Figure 3 are an example for the extensive recordings which were done during that time. Other approaches for the interpretation of the huge amount of results apparently were not established.

It was commonly known that a difference exists between the standard test lightning impulse voltages and the in reality occurring impulse-like overvoltages. With increasing transmission voltages this became more and more important for the development of the insulation of electrical equipment.

Besides a discussion on the experimental investigations of the physical understanding of these phenomena, a section with the approach of the estimation of the time dependent behavior of the breakdown voltage in air gaps is included as well. Considering the wide range of measurements in several high voltage test fields it is surprising that first in the 1950th a theoretical approach for the quantitative estimation of the insulation behavior of a technical electrode configuration in air was published for example by [8], [9].

Andrew R. Jones, an employee of Westinghouse Electric Corporation in Pittsburg Pa, published the results of his master thesis with the title „Evaluation of the Integration Method for Analysis of Nonstandard Surge Voltages“ in 1954 [9]. He emphasized the issue of a standardized impulse test voltage to gain experimental experience about the influence of not standardized impulse forms on the electric strength of insulations. „This influence has been demonstrated by Hagenguth for a wide range of wave shapes applied to rod gaps“[7].

For the quantitative evaluation of this behavior, impulse curves of any kind were compared with the, in the US usual, impulses 1,5/40 μs. As a suitable method for this task he investigated the „Integration Method“ by R.L. Witzke and T.J. Bliss published in 1950. In his detailed work the topic of the question how arresters should be integrated in high voltage transmission grids is discussed. This discussion was in the background to establish a protection of transformers connected by cable against traveling waves caused by lightning. The behavior of the insulation was not part of his publication.

As a result of the experience and not physically based thoughts the parameter of stress “Disruptive Effect DE” was introduced:

\[ DE = \int (U(t) - k_1)^{k_2} \, dt \]  

(1)

In this equation \(U(t)\) is the instantaneous value of the voltage at time \(t\), \(k_1\) and \(k_2\) are used as arbitrary parameters.

Jones contribution is the adoption of this equation, which was proposed for the stress of grid structures. This was verified by many measurements on rod spark gaps. His result was: „The „Integration Method“ provides a valuable tool for evaluation of surge voltages of any shape in terms of the standard insulation data with 1.5/40 μs shape surges“.

The arbitrary definition of the parameters \(k_1\) and \(k_2\) gives this method a high flexibility for the correction. However the DE misses a plausible physical meaning obvious through the undetermined dimension. To avoid this disadvantage the Severity index “SE” was introduced. This index consists of the \(k_2\)-square of the quotient of the breakdown voltage gained during the experiment with a standardized impulse voltage. With this index DE gets an undetermined dimension however the calculation of this value is time consuming for which reason Jones used for the interpretation an analog computer. Figure 5 (source Figure 4 of [9]) shows as an example of the analyses of a 50 inch rod spark gap. With the correctly chosen values of \(k_1\) and \(k_2\) the volt-time curve approximates the measurements quite well.

Figure 5. Impulse voltage curve analyses of a 50 inch rod spark gap, Jones[9]

a) standard volt-time curve 1.5 / 40
b) check on the integration constants \(k_1\), \(k_2\) (points indicates measurements and their correction)

V. EQUAL-AREA CRITERION ACC. TO KIND 1957

In contrast to the integration method with two arbitrarily chosen values described in chapter IV which is used by Jones 3.

for the calculation of the disruptive effect, D. Kind uses at first a simplified physical model of the breakdown process [10].

With a simplified model for the development of the discharge channel in a spark gap without space charge, it may be a streamer or a leader, it is considered that the velocity \( v(x,t) \) is proportional to the local field strength, when the field strength is greater than a certain critical value. Since the field strength under the given requirements is strictly proportional to the impulse voltage it is valid to write:

\[
v(x,t) = K [U(t) - U_b] = \frac{dx}{dt} \quad \text{considering} \quad U(t) \geq U_b
\]  

(2)

However the value \( K \) has to consider the geometry and the mechanism of the discharge. Following the separation of the variables is obtained:

\[
\int_{s=0}^{x} \frac{dx}{K} = \int_{t=t_1}^{t_1+t_d} [U(t) - U_b] \, dt
\]

(3)

The channel with the sparkover distance \( s \) begins at the time \( t_1 \) when the impulse voltage \( U(t) \) exceeds the reference voltage \( U_b \). The left side of the equation has a constant value for every geometry.

The distance-time integral results in a volt-time area \( A \) in extension to the formative time lag of the discharge named as formative time area [10].

\[
\int_{t_1}^{t_1+t_d} (U(t) - U_b) \, dt = \text{const} = A
\]

(4)

Figure 6 is a graphic schema of the area law for complete and cut-off impulse voltages. (This Figure is taken from the original paper where the formative time area \( A \) is referred as F)

This voltage time area law is called in English “Equal-area Criterion“. As a good approximation for the reference voltage \( U_b \) the peak voltage of the a.c. breakdown voltage can be used. This is also usable in strongly inhomogeneous fields even if the complete discharge is developed after longer preionization.

The experimental verification of this criterion was tested with different impulse voltage curves before publishing [10]. In order to test this criterion at that time the newly developed cold cathode oscillographs for the measurements of time dependable curves under 1 µs were a necessary requirement. To verify the criterion up to the MV range the published literature could be used.

The experimental verification of this criterion was of course a precondition for any reasonable consideration about a practical application. Beyond own measurements, results from independent external investigators have to be compared. Despite the great number of published volt-time characteristics only few were eased in comparable quality in short-time measurements. The work by Hagenguth and cooperators, as referred to in Chapter II, offered material for quantitative comparison.

Figure 7 shows volt-time curves from results with 50 inch rod sparkgaps taken from Figure 3 in comparison with the calculation with the equal-area criterion. Both results were compared to standard-impulses and as well as step-impulses, they can be rated as rather auspicious.

The described model conception for the growth of a streamer discharge led to the equation of the equal-area criterion. Even if a general validity of this simple physical model couldn’t be expected, the practical usability was confirmed in many cases. Next to the general transferability this equation has the advantage of clarity through the fulfilment
of the evident borderline cases of the beginning of the discharge channel and the earliest possible complete discharge.

The above mentioned experiments to check the validity of the equal area criterion were performed with all reasonable geometrical types of electrodes, as far as own equipment was available or could be taken from literature [10]. Of special interest was of course the form of the electric field, the degree of symmetry and the polarity.

The relative area \( A/U_b \) was found to be a characteristic quantity for the degree of inhomogeneity of any gap. The value of \( A/U_b \) for airgaps in nearly homogeneous fields is about 10 ns, in extremely inhomogeneous fields in the order of 1000 ns. It could also be understood as a measure for the formative time lag of the breakdown\(^4\) and appears to be an interesting observation for further research.

The sustained interest in the behavior of electric components in relation to lightning stroke phenomena led to further worldwide research activities. Among many others, Wagner and Hileman from Westinghouse, Electric Corporation, followed a general approach from the physics of stroke to the insulation. Four years after the establishment of the equal-area criterion, they published calculated time-lag curves for various gaps within a series of papers. Figure 8 is an example for rod-rod gaps [11]. Their measurements and calculations show the independence of time lag from gap length. The abscissa displays relative overvoltage \( U_d/U_b \). This corresponds with the equal-area criterion in a wide MV range where the leader discharge leads to the breakdown.

Since then, this criterion has been used as a clear model for a simplified description of the impulse curve of gaseous insulations and thus has done an important contribution to the insulation coordination in high voltage transmission grids.

The approval of this criterion in practical applications has inspired several scientific investigations with the objective to confirm its practical usefulness and the effect of limits in the preconditions. Various attempts were made to discuss the criterion on the general basis of gas discharge physics [12]. It was made visible that not even only air but also other gases like \( SF_6 \) could be rated with this law [13], or possibly even for discharge in fluids. The validity for breakdown was shown for higher probability [14] and also for applications beyond the classical insulation coordination [15].

VI. COMPUTER-AIDED EVALUATION OF LEADER PROPAGATION

Shielding failures with direct strokes to the phase conductors or back-flashovers of the overhead line insulators produce lightning overvoltages. Lightning incidence data and critical lightning strike parameters have to be considered. But the tower insulators play a key role and the magnitude of line overvoltages is determined by their flashover characteristic. Actual research is on the way to improve the knowledge about

\[ U_{f0} = 400 \frac{kV}{m} d + 710 \frac{kV}{m} d \left( \frac{t}{1 \mu s} \right)^{-0.75} \]  

As example the flashover voltage of a 5 m insulator string is calculated. The volt-time curve is shown as a reference in Figure 8. For comparison the time to flashover is shown in a limited range between 0.5 and 3.0 \( \mu s \). The 50% flashover
voltage above 3 MV is also shown which is the calculation result of the leader propagation model.

The equal-area criterion demands a reference value for the minimum voltage. In accordance to equation (5) a minimum voltage of 2 MV and a voltage-time area of 3.4 Vs are taken as calculation parameters. The rising flashover voltages for standard impulses are overestimated by this procedure as shown by the squares in Figure 9.

\[
\frac{dx}{dt} = k \cdot u(t) \cdot \left( \frac{u(t)}{d - x} - E_0 \right)
\]

(6)

The leader starts after the streamer bridges the gap and sufficient high average field strength \(E_0\) is available for the leader development. The leader propagation velocity given in equation (6) depends on the surplus of the average field strength along the remaining leader path before bridging the gap.

This formula describes an empirical model, discussed in many papers [20]. Because leader velocity is easy to calculate, the formulae is commonly applied [21]. Two parameters are needed to adapt the leader velocity to experimental values. The field strength limit \(E_0\) and a constant \(k\) describing the required energy density for leader propagation. The parameters are given for two different classes of insulators [17]. The higher electric stress due to back-flashover is produced at negative polarities.

But the application of the parameters is limited to the experiences in the past. New insulator and transmission line concepts, EHV and HVDC applications demand flashover calculations with new boundary conditions [16], [19-21], [22]. An addition of parameters for new insulators is discussed, because there is a lack between experimental and calculated data. It seems also to be a task to find proper methods for atmospheric corrections [16]. A first approach for HVDC string insulators with a length of 7 m leads to a reduction of the parameter values to fit the experimental voltage-time curves. These can also be found in literature from the eighties and an overview is given in [23]. Variation of parameters is a crucial option and should be used carefully. It is important to know about the parameter sensitivity [24, 25]. Lower values for the parameter \(k\) reduce the leader propagation velocity. And the reduction of the field strength limit \(E_0\) shifts the v-t curves to lower values. These parameters estimate the electric field development during leader propagation. It seems to be a demand for new calibration of the leader propagation parameters in the coming time.

**VII. CONCLUSION: 100 YEARS OF SCIENTIFIC RESEARCH**

Marx and many other pioneers in the field had to show remarkable intuition in the physical interpretation of the electrical breakdown in air regarding the rare possibility of short term measurements. He published under the title of "Maximum Breakdown Voltage" that with the increasing steepness of the test voltage, the breakdown voltage level increases as well: "The voltage can rise higher with a steeper increase during the pre-ionization".

The state of the development is described by [26] and translates to: "The stress in electric components caused by traveling waves is emulated using impulse voltages. The generation of these impulse voltages up to several MV was made possible with the multiplier circuit of E. Marx. The investigations on overvoltages generated with this circuit were supplied by several developments in this time, for example the cathode ray oscillograph. This allowed in detail to picture a time dependent curve of overvoltages."

The reason for failures of insulations with unknown overvoltages could not be rated in measurements at first. The generation of high impulse test voltages and later the definition of time dependent curves created the foundation for the research of electrical strength of high voltage equipment.

In the 1960s the growing need for the electrical power caused the introduction of the transmission voltage of 1200 to 1500 kV. The uncertainty regarding the electrical strength of long breakdown distances in air was an important research topic. This was investigated in an international cooperation in the French UHV-laboratory “Les Renardières”. Here the equal-area criterion (“Flächengesetz”) provided good results for breakdown distances up to 10 m [27].

The development of the electronic computing with the coming 21th century helped the successful processing of tasks in the insulation coordination.

In the early times of the high voltage transmission grids the interest was mostly in experiments for measuring the voltage-time characteristic with standardized impulse voltages for different technically relevant insulations. This is discussed in chapter I and II. After the insight that the electrical strength depends strongly on the impulse curve the evaluation of temporally arbitrary stresses, which can be caused by lightning discharges, presented a new field of work which is discussed in chapter III and IV.
The leader propagation model allows some more insight in flashover voltage origin. But it is only a simplification which is sensitive to parameter variations. It seems to be a demand for new calibration of the leader propagation parameters in the future.

In Chapter V a simple physical model is proposed “starting from the first principle of discharge process in an air gap” [19]. It let to the equal-area criterion which opened a self-reliant purposeful concept for further research [10]5. Finally, the leader propagation model in chapter VI allows some more insight in flashover origin. It seems to be a demand for new insulators of transmission lines to evaluate the right leader propagation parameters in the future. Looking back to Hagenguth 1941[7], engineers today do not renounce any more "to translate data in electrons, ions and terms of photo ionization".

After 100 years of successful research and development coming from the lightning discharge this leads to a successfully established protection against damages of electrical equipment in our current high voltage transmission grid. „Because of the increasing importance of the effects of the nonstandard lightning voltage waves on power apparatus“ an international review of research until 1994 was established. It includes a biography of not less than 207 papers [19] and could be extended until today. Evidently this confirms 100 years of successful research and development not only to successfully established insulation coordination but also to improved physical knowledge of gas discharge.

REFERENCES


5 The early checks of the limits of validity for the criterion suffered from the fact, that the uncertainty of measurement results were not quoted according to nowadays demanded IS0/IEC standards GUM. This obstacle could only be overcome by new precise measurements with uncertainty budget.