Evaluation of composite voltage test parameters

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Evaluation of composite voltage test parameters in the case of the combination power frequency and switching impulse

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***Abstract*— The integration of renewable energy sources into the power grid and the extension of power transfer capabilities is one important step towards a reduction in CO2 emissions, a sustainable infrastructure and environment friendly power generation. In the electric grid this is causing a shift from the centralized generation of energy by big rotating AC generators towards more complicated, distributed, often semiconductor-based grid components using DC power in the process of power generation and often higher system voltages. The latter is underlined by the trend of ultra high voltage (UHV) power transmission. This leads to the need of more adequate, adapted test principles for the examination of the capabilities of grid components. In this context the work on the next revision of the standard IEC 60060 series considers the implementation of combined and composite voltages for impulse voltage tests. Until now there is no uniform procedure for the evaluation of the parameters of these novel test voltages. In particular for the case of more complex composite wave shapes. The Example this paper features is an impulse superimposed to a 50 Hz AC signal which record does cover only a small number of whole periods. In this paper we would like to investigate approaches in how to obtain concise and comparable results when working with combined and composite test voltages. These voltages consist out of lightning impulses (LI) or switching impulses (SI) superimposed to a conventional power supply voltage that is either an AC or a DC Voltage. Subject to this investigation is also the use of nonlinear regression in the process of the evaluation.**

Keywords—composite, impulse, high voltage, test, calibration

I. Introduction

The upcoming technology of HVDC and UHV Transmission incorporates several challenges for the energy grid related Metrology. At the same time many grid components like inverters for renewable energies incorporate semiconductors that can be prone to voltage peaks. It is necessary to meet the requirements of a growing demand for energy transmission over increasing distances with higher capacities. This of course incorporates the need for higher voltage levels. HVDC transmission technology becomes even more relevant concerning economic factors. While HVDC power transmission is higher in fix costs it is lower in costs per distance which is why it is potentially the preferred approach for the connection of offshore wind farms [1]. This underlines the necessity for the adaption of grid component testing and the calibration of test equipment to these new technologies and higher voltage levels. To date the testing of grid components is divided into separate fields of measurements, that are performed individually. To give an example, components like transformers or voltage dividers for AC are tested with AC and, commonly on top of that, with lightning impulses (LI) or switching impulses (SI) to examine their resilience against voltage peaks or their ability to measure transients. In the role of a National Metrology Institute (NMI) the Physikalisch-Technische Bundesanstalt (PTB), as the NMI for Germany, this is relevant for offered calibration services in the field of high voltage metrology. The described separation of impulse tests and withstand voltage tests leads in some cases to the calibration of different scale factors for AC and impulses.

With the approach of combined and composite waveforms the test conditions are closer to the situation a device under test would experience in during their actual application leading to a more precise prediction of performance in its lifespan. Especially interesting is this more realistic test condition for the evaluation of performance for dielectric or insulating materials used in grid components. Further examples for the necessary application of combined and composite voltage test are HVDC cable test and the testing of gas insulated high voltage systems. The latter can be seen as an essential technology for HVDC transmission [2]. As an example, there are phenomena that occur especially when testing gas insulated high voltage systems with combined wave shapes. These phenomena result in a reduced breakdown voltage. When an insulating material is located in an electric field a transient shift of charging current can be measured. For DC, after this transient the current falls to a low static current which is reached asymptotically. The time to reach this asymptotic value is influenced by the material used and its conductivity [3]. While this phenomenon is under investigation for DC. Applying this information to AC lets us conclude that it can bring valuable information about dielectric strength of a certain device and if it can withstand transients without failure that it will may experience during operation. Another example underlining the necessity of grid component testing especially with AC and impulses is the investigation of lightning strikes in overhead lines or other active grid components. In source [4] an investigation was made concerning this topic.

The reliability of high voltage electricity grids depends on the adequate testing of grid components. This is why there is an urgent need for traceable measurement systems for composite and combined wave shapes that can be directly attached to the device under test [5]. At the same time this is the reason for the increasing use of combined and composite voltage tests. These two terms describe the combination of several (commonly two) test voltages that are applied to a device under test. Most of the time an impulse is combined or superimposed to either a DC or sinusoidal AC supply voltage. The combined and composite voltages distinguish in the way the device under test is arranged relative to the voltage sources within the test setup. While combined voltage testing typically involves the application of two separate voltages to a test object with separate input terminals for each voltage, composite test voltages are applied to a test object with only one input terminal [6]. The generation of superimposed voltages can be accomplished by using existing impulse generators in combination with regular voltage sources [7].

To date there is no standardized procedure how to evaluate the parameters for composite waveforms consisting of either a lightning or switching impulse and an alternating or direct current supply voltage [8]. This paper aims to propose a routine for the evaluation of these measurements.

One key element of the evaluation is the data analysis which should provide a possibility to distinguish the power supply voltage from the transient impulse. In the case of an impulse superimposed to a DC voltage this task is quite trivial. The DC voltage represents a simple offset to the impulse. Small oscillations on the DC portion, so called ripple, can be determined if desired and should not interfere with the evaluation of the impulse parameters. More complex can be the case if AC and impulses are combined because the superposition of these two waveforms changes their appearance in the diagram and thus cannot be analyzed by existing evaluation tools that are typically designed to process only one of the waveform types. Especially problematic can be the case of AC superimposed to a SI which time constants are in the same magnitude of the ACs frequency. After this first step of distinguishing the signals, the software generates two sets of data out of the measurement. One data set resembles the isolated impulse and the second resembles the AC component. The impulse data set should be possibly close the following double exponential function that describes the charge and discharge of an impulse generator circuit using an RC configuration to form the voltage slope.

$$u(t) = U\left(e^{\frac{-(t-t_\mathrm{d})}{\tau_1}} - e^{\frac{-(t-t_\mathrm{d})}{\tau_2}}\right) \quad [6]$$

While high frequency components are filtered and dampened by the IEC 60060-1 [9] evaluation with regards to insulation material effects, low frequency components can potentially falsify the results of the impulse evaluation. The data can then be analyzed by standardized algorithms described by the IEC 60060-1 [9] to determine their result parameters such as:

- Rise time T_1 which evaluated by linear regression of a line through the points of 30 % and 90 % of the peak voltage in the rising slope of the impulse. T_1 is the period of time between mentioned lined crossing the x-axis and reaching the 100 % voltage value of the impulse. This parameter is primarily used for LI.
- Time to peak value T_p for the time from the beginning of the impulse until the voltage reaches its peak value. This parameter is primarily used for SI.
- Time to half T_2 for the time from the beginning of the impulse until the voltage slope has fallen to half of the impulses peak value after the crest.
- Peak value U_p .as the maximum voltage value of the impulse waveform

If possible the evaluation should be robust against other forms of distortions such as noise or superimposed oscillations that don't belong to the signal which evaluation is desired. The data set resembling the sine voltage shall be used to determine the frequency and amplitude of the AC signal.

II. METHOD OF EVALUATION

The work in this paper is one result of work package 1 of the EMPIR Project HVcom². The task involved that every participating institute to conduct an evaluation on a set of recorded waveforms with their evaluation software. If none was existent at that time the institute had to develop a software for this task. The results shall then be collected and compared to find the best performing practice of the evaluation of combined and composite waveforms. In the case of the PTB, the existing software had to be extended for the measurement data that resemble switching or lightning impulses superimposed to AC voltage. When intending to analyze AC voltage with impulses the combined peak voltage depends on the timing of the impulse respective to the phase of the AC voltage and the polarity of the impulse. The solid line in figure 1 shows an example of the waveforms that were to examine. In this case the signal consists of an AC and a SI voltage. The waveform represents one of the datasets generated and used in the work package 1 of the EMPIR project HV-com² (19NRM07). This waveform was measured by the reference system of the HV-com² Project partner Tampere University in Finland. The waveform was generated with an AC source, a blocking capacitor and their impulse generator.

The first approach that can be feasible benefits from the repetitive nature of the AC power signals sinusoidal waveforms. The sine frequency would be recorded or observed in a period where no transient impulse is present. A second record would be made to save the sine wave with the superimposed impulse. The records could be subtracted from one another to obtain an isolated waveform of the transient impulse that can be analyzed accordingly. This concept involves the problematic aspect of timing. While modern oscilloscopes or digitizers can trigger accurate enough to start a record at a sufficient identical phase angle of the sinewave it is possible that the transient signal triggers the record too early and a not phase identical record would be made. In this case the procedure cannot lead to sufficient results. While it would be applicable if it is known that the transient starts at a certain position of the sine, for example during the peak of the sine, it is desired that an algorithm works independently from the timing between sine and impulse. Additionally, it is more practicable to design a procedure that works with only one record for the entire evaluation. This way the measurement of sine and transient are examined for the same point in time.

The proposed algorithm for the measurement of lightning impulses described in the IEC 60060-1 [9] incorporates a data preparation using a least-squared error method called Levenberg-Marquardt-Algorithm (LMA). This concept involves a mathematical model of the double-exponential impulse as the starting point for this operation. The LMA varies the mathematical variables of a parametric model function. This model function should be a mathematical representation of the searched waveform. The goal of the LMA is the optimization of the least squared error which is derived by the comparison of the model with the recorded waveform [10]. The LMA needs starting values for its search, it varies them and iterates until the error is smaller than a certain margin. Hence the mathematical model is negligible close to the measurement data. This way a mathematical reconstruction of the measured curve is created in terms of time constants, delay and peak value.

Our approach for the evaluation is to apply the same concept to find the properties of the sinusoidal power signal. To achieve this, we execute the LMA with a sine wave as a mathematical model and let the LMA search for the best fit in terms of frequency, amplitude and phase. Figure 1 shows the fitted sine as a dashed line.

Then we can subtract the mathematically fitted sine from the composite measurement data. What we get after this step is already a rough isolated impulse measurement that can be processed by the IEC 60060-1 [9] algorithm for lightning impulses. This waveform is depicted in figure 2.

Some of the recorded waveforms used in the EMPIR HVcom² (19NRM07) project showed harmonics of the power frequency clearly visible after the removal of the base frequency as remaining oscillations in the impulse waveform. These multiples of the fundamental frequency can also be removed or at least dampened with the same approach using the LMA with an optional extra step before feeding the extracted impulse waveform into the IEC 60060-1 [9] evaluation. This can be done by searching for multiples of the fundamental frequency and setting these multiples as starting parameter for the LMA. This way we can enhance the accuracy of the evaluation for the parameters of the impulse by processing a less distorted signal with the algorithm of the IEC 60060-1 [9]. The Algorithm in the standard only implements the use of a low pass filter. This implicates that the oscillations that origin as harmonics of the superimposed sine voltage, and thus technically don’t belong to the impulse would be regarded by the impulse evaluation. It can be worth considering to eliminate these harmonics. In other cases, it can be desired to take these oscillations into account while evaluating the impulse for example when investigating insulating materials. In cases like calibrations, it might be unwanted. To decide whether the harmonics shall be part of the impulse or if it is beneficial to remove the harmonics by the numerical method should be a decision of the individual use case. Figure 3 shows the isolated impulse after the reduction up to the seventh harmonic. It is possible that the contribution of the harmonics is time varying in amplitude. To counter this problem, it is possible to emphasize the LMAs regression on the part of the waveform that is crucial for the further evaluation.

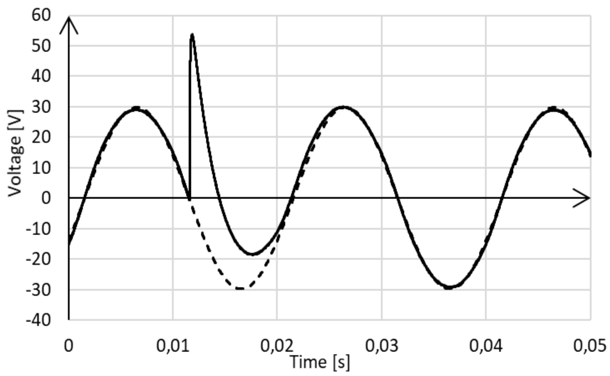

Fig. 1. Composite waveform (solid line) with fitted pure sine wave (dashed line)

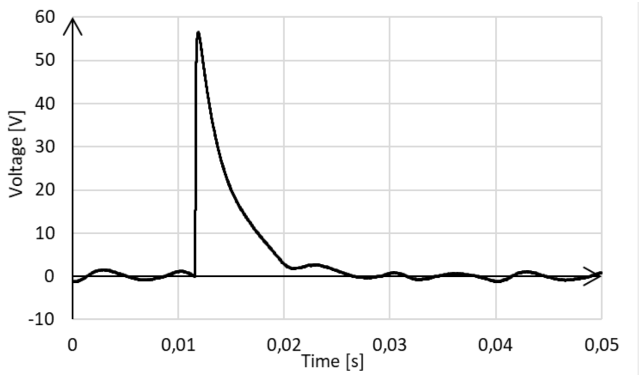

Fig. 2. Isolated impulse obtained by subtraction of sine frequency from composite waveform

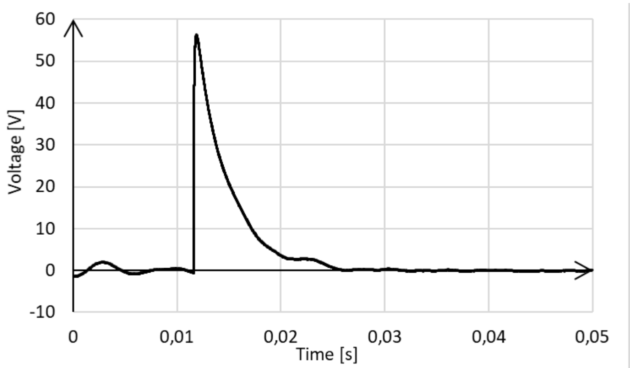

Fig. 3. Isolated impulse after reduction of harmonics

III. VERIFICATION

To verify the results of our method we generated a sinewave and added a reference impulse listed in the standard IEC-61083-2 [11]. The mentioned standard comes with a piece of software as a Test Data Generator (TDG) capable of generating a number of different types of impulse waveforms with the purpose to test evaluation software. The TDG software allows to enter key characteristics of the aimed digitizer/acquisition hardware like noise, voltage resolution and sample rate. Within the standards annex there is a table given documenting the peak voltage as well as timing parameters for the impulse waveforms that are selectable in the TDG software. The characteristic parameters of a SI waveform are marked with U_p for the peak voltage, T_p for the time to peak value and T_2 for the time to half value after the peak. The superposition of a known sine wave and a TDG generated impulse gives us a superimposed waveform with known reference parameters to test our software evaluation.

We chose the TDG-waveform “SI-A2” for our test. The generated TDG impulse has the following Reference parameters:

- U_p = 987,67 V
- T_p = 19,89 µs
- T_2 = 1321 µs
- Sample rate: 800 kS/s
- Resolution: 12 Bit

The sine waves parameters are:

- f = 50 Hz
- û = 1000 V
- Sample rate: 800 kS/s
- Record length: 50 ms

Figure 4 shows the superposition of the waveforms. The beginning of the impulse is at 10 ms on the x-axis. The dotted line is the fitted sine by our new evaluation procedure.

For the evaluation we disabled the search for harmonics of the power frequency because we can guarantee that there are no harmonics in our generated waveform.

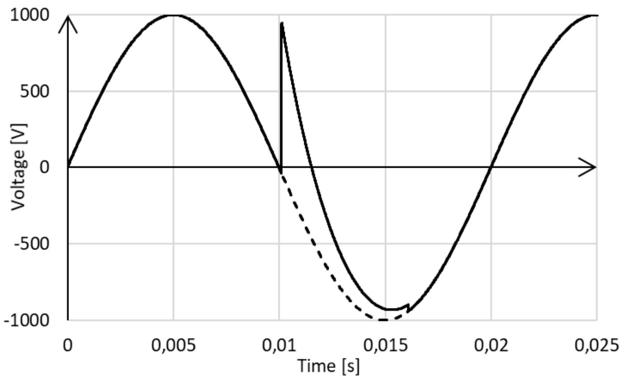

Fig. 4. Generated reference composite voltage

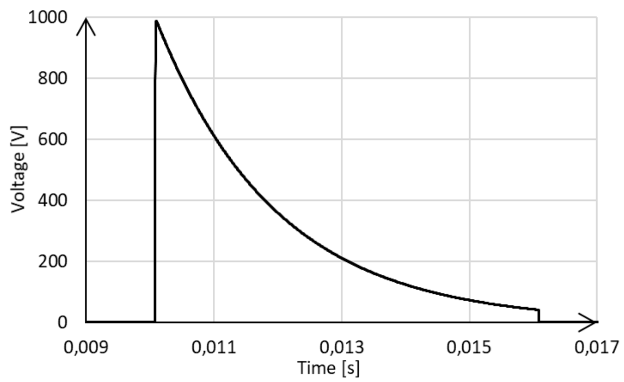

Fig. 5. Isolated reference impulse

The evaluation gives us the following extracted impulse in figure 5. It is not possible to see artefacts of the sine wave on the extracted impulse within the important period of time. The extracted waveform is visually not distinguishable from the original shape of the TDG impulse “SI-A2”. This is a first proof of concept for our evaluation.

Additionally, we added noise to our generated test data to simulate a real-world recorded signal. The test data without noise is perfectly describable by mathematically defined functions. Noise will test the robustness of the method against distortions. The noise level we chose is 1 % of the peak-to-peak value of the sine wave. Our simulated noise is generated by adding a random number in the range of the mentioned 1 % to every sample of the waveform.

The parameters of the fitted sine wave are presented in table 1. Table 2 summarizes the results of the evaluation.

TABLE I. SINE VERIFICATION RESULTS

	U_p [V]	*f* [Hz]
Reference	1000	50
SI-A2 superimposed (Deviation)	1000 (0 %)	50 (0 %)
SI-A2 superimposed 1 % noise (Deviation)	999,799 (0,0201 %)	50,0008 (0,0016 %)

TABLE II. IMPULSE VERIFICATION RESULTS

	U_p [V]	T_p [µs]	T_2 [µs]
Reference	987,67	19,89	1321
original SI-A2-evaluation	987,679	20,0485	1321,88
SI-A2 superimposed (Deviation)	987,679 (9,112 ppm)	20,0485 (0,797 %)	1320,62 (-0,029 %)
SI-A2 superimposed 1 % noise (Deviation)	997,145 (0,959 %)	20,4543 (2,837 %)	1287,26 (-2,554 %)

IV. SUMMARY

In this paper we showed a proposal on how to evaluate composite wave shapes especially in the complex case of superimposed voltages with AC component. Our algorithm involves the following steps:

- Analysis of the sine proportion using the LMA
- Subtraction of the sine from the superimposed voltage gives us an isolated impulse
- Optional search and subtraction of harmonics if desired
- Evaluation of parameters using IEC 60060-1 impulse evaluation

When working with this method we pointed out the following issues that can be object to further investigations:

One issue would be the dependency of the phase angle of the start of the impulse respectively to the sinewave. Everything that changes the appearance of the sine significantly is leading to an increased deviation of the results the LMA is providing to reconstruct the sine wave. We observed different deviations depending on the timing of the two superimposed waveforms and their shape. Also, different polarities of the same impulse can affect the result in a more or less significant manner.

The second issue would be that the lengths and size of the records with a LI can be problematic. When working with nonlinear regression methods like the LMA the workload increases exponentially with the quantity of the sample points. To be able to process a sine wave with a fast impulse it is necessary to involve multiple periods of the sinewave on the one side but still provide a record with a sample frequency high enough to depict the risetime of the impulse. This can lead to file sizes that can be difficult to handle even with state-of-the-art software and hardware. The outcome can be a long processing time or even a memory overflow. The latter is often caused by development systems memory limitations, like it is with LabVIEW the case.

Another important aspect is noise and distortions, after adding noise we found significantly higher deviations. Also, if the shape of the sine is warped in any way that is not possible to be modeled in a trivial way, by harmonics for example, it will have an impact on the results.

In the use of numerical optimization methods in measurement data analysis lies a big potential for non-trivial measurements where one key task is the identification of certain properties within a set of measurement data. A hand-crafted evaluation of time parameters for instance is no longer adequate and time consuming. Automated, computer aided software, that solely compares voltage values of samples is prone to errors if the measured signal is disturbed or only poorly repeatable. All this applies to the measurement of transients in high voltage metrology. Nonlinear regression with the help of methods like the LMA creates the opportunity to apply another factor of a priory knowledge to the measurement evaluation that otherwise is only possible by hand-crafted evaluation if the performing person has the skill to estimate an average curve of a disturbed signal for example. The LMA represents a possibility of automating this task and by being a mathematically algorithm a repetitive standardized method. On the other hand, numerical regression can also fail if the underlying data is not sufficiently present. The application of the described methods requires the staff performing the measurement to have a certain knowledge about the way the regression is functioning in order to classify the quality and validity of the results.

The results show the suitability of the evaluation method for superimposed voltages with AC component. One important issue for the comparability of these measurements would be the integration of an evaluation routine into a standard to ensure the comparability of measurements across different laboratories and institutes. The longterm goal is the establishment of a uniform and traceable measurement procedure for combined and composite wave shapes. The findings of this paper are applicable in practice for calibration institutes and laboratories that are dealing with high voltage tests and power grid components. More specific we presented a possible way to evaluate complex composite wave shapes. This is relevant due to the novelty of this kind of tests and their rising demand. The latter is induced by the integration of renewable energy sources and new technology for power transmission by using HVDC and higher system voltages in new generation power lines.

V. Acknoledgement

Parts of the presented work are used in the project 19NRM07 (HV-com²) which has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

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