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CALCULATING THE PARAMETERS OF FULL LIGHTNING IMPULSES USING MODEL-BASED CURVE FITTING

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ABSTRACT

A brief review is presented of the techniques used for the evaluation of the parameters of high voltage impulses and the problems encountered. The determination of the best smooth curve through oscillations on a high voltage impulse is the major problem limiting the automatic processing of digital records of impulses. Non-linear regression, based on simple models, is applied to the analysis of simulated and experimental data of full lightning impulses. Results of model fitting to four different groups of impulses are presented and compared with some other methods. Plans for the extension of this work are outlined.

Keywords: Model-based parameter evaluation, curve-fitting, digital signal processing, high voltage impulse testing, impulse measurements.

INTRODUCTION

Many laboratories are now using digital recorders to record impulses in routine high voltage tests. The requirements and tests to qualify a digital recorder for use in impulse testing have been standardized [1] and work has started on preparing a guide on applying digital signal processing to parameter extraction and other aspects of analyzing records [2]. Many techniques, ranging from simple algorithms to quite sophisticated techniques, are already yielding increased precision and providing new approaches to both laboratory and on-site testing of high voltage equipment. For smooth impulses, simple techniques give results with sufficient precision to be compatible with the requirements of the IEEE standard on high voltage test techniques [3]. However, when there are oscillations on the front of the impulse a mean curve has to be drawn through these oscillations and the parameters are calculated from this smooth curve. Two approaches have been used to generate this smooth curve: curve fitting using multiple linear regression [4] and digital filtering of the record (for example, [5]). The method of multiple linear regression given in [4] depends on the separate determination of two exponential constants while digital filtering degrades the front time. The determination of the best smooth curve through oscillations on an impulse is the major problem limiting the automatic processing of digital records of impulses.

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In comparative tests of high voltage impulse measuring systems it has been found that the precision of measurement of front times is much lower than that achieved for peak voltage and time to half-value [6]. This can be attributed to small differences in the way that the two systems transmit front oscillations. Hence a method of calculating the front time which is insensitive to these oscillations is needed. In addition, it is of interest to increase the resolution (and use this increased resolution to increase the precision and possibly the accuracy) of such comparative measurements.

This paper considers the application of simple models of the high voltage circuit to derive analytic approximations to the measured impulse. Non-linear regression analysis is then applied to fit the recorded data to the derived function. These analytic approximations are not new. Indeed, the present IEEE standard is based on them [3] and many papers have used these functions as assumed inputs when evaluating the errors to be expected from measuring systems (for example, [4, 7, and 8]). However, the authors believe this paper is the first systematic investigation of their use with non-linear regression to derive the parameters of measured impulses. Earlier work by one of the authors [9] used a variety of programs (which were developed in-house to fit sinusoids [10]) but these programs were either not sufficiently robust or too slow. Nevertheless, they established the validity of the method and provided information on several aspects of the problem.

In addition to the major objectives discussed above, a subsidiary aim is to provide a public-domain program which can be used on-line on a desk-top computer to provide consistent and accurate automatic data reduction for routine operation in industrial applications. This requires that the program should be developed to run on readily-available desk-top computers using inexpensive software and that it should be open, so that users may incorporate their own modifications. Long term aims are to consider how non-standard impulses should be treated and to consider whether the required parameters and their definitions are the most appropriate for automated application to digital records. The parameters which are presently in use were defined for use in reading oscillograms and therefore had to be relatively simple to evaluate so that the time spent in reading oscillograms could be kept within tolerable limits.

PARAMETERS TO BE EVALUATED AND THEIR DETERMINATION

For a smooth impulse, the parameters to be evaluated are defined as follows:

1. Peak voltage V_p — the difference between the top magnitude and the base magnitude, multiplied by the scale factor of the system. (The peak voltage does not usually correspond to the maximum value in the digital record).

2. Front time T_1 — $1.67(t_{90} - t_{30})$, where t_{30} and t_{90} are the times when the impulse first reaches 30% and 90% of its peak value, respectively (see Figure 1).

3. Time to half-value T2 — $(t_{50} - t_0)$, where $t_0 = t_{30} - 0.3T_1$ is the virtual zero and t_{50} is the time when the impulse decays to 50% of its peak value (see Figure 1).

4. Time to peak T_p — the difference between the time of occurrence of the peak value and the virtual zero. This parameter is usually defined and used with switching impulses only. However, because there are problems in its determination and because the curve-fitting routines described here are equally applicable to switching impulses, its evaluation is included in this work.

These definitions are unambiguous and easily applied to ideal smooth impulses. However practical impulses may be perturbed by electromagnetic noise and by oscillations. When an analog record is used, only a limited amount of processing is practical and the values obtained depend on value judgements made by the operator. When a digital record is used, the whole file is available for processing and this processing is independent of the operator once the algorithms to be used have been selected.

Before introducing the non-linear regression curve fitting method it is useful to review some of the other methods presently in use. The base magnitude is usually determined either as the dominant level which occurs before the start of the impulse or, more accurately, as the mean value of a number of samples before the start of the impulse. When pre-trigger recording is available these samples can be taken on the same record as the impulse thus eliminating short time variations which could affect the determination of the base magnitude from a separate record with zero input.

Several examples of the region in which the peak value occurs are shown in Figure 2. For reasonably high resolution recorders (8 bits or greater) it is possible to take the maximum value as corresponding to the peak value without causing too large an error even though this approach will always give a slightly high value to the peak value. A more precise value can be obtained by taking the mean value of some number of samples, such as the range of occurrence of the maximum value. However, if this number is too small then the estimate of the peak value will most likely be too high while if this number is too large then the estimate of the peak value will most likely be too low. In any case, random changes from record to record will cause variations and these will be largest for small values of the number of samples over which the mean value is taken. One proposed approach is to identify the first occurrence of the maximum value and to take the mean over five samples from the sample before this first occurrence to three samples after it [11]. This approach takes some account of the asymmetry of the impulse but it should be noted that this asymmetry will be smaller for high resolution records and that the position of the first occurrence of the maximum value is influenced by noise. An estimate of an upper limit to the number of samples which should be averaged can be calculated from the expected rate of change near the peak value of the nominal input [12]. Alternatively, this number can be determined by inspecting the record of the impulse but this method is to some extent subjective and not readily automated. While the histogram method [13] is most suited to flat-topped pulses it can also be applied to rounded impulses provided the sample rate is sufficiently high to give enough samples near the peak value.

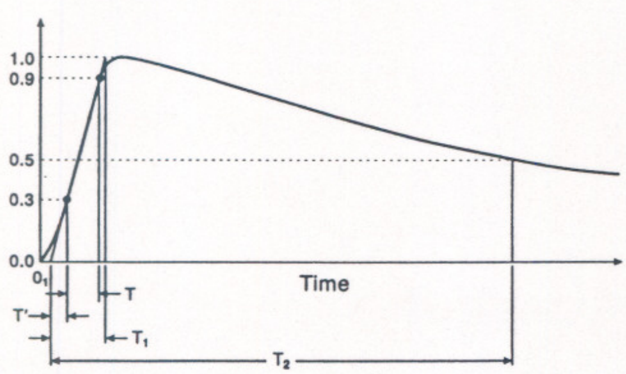

Figure 1. Illustration of the definitions of the time parameters of a full standard lightning impulse.

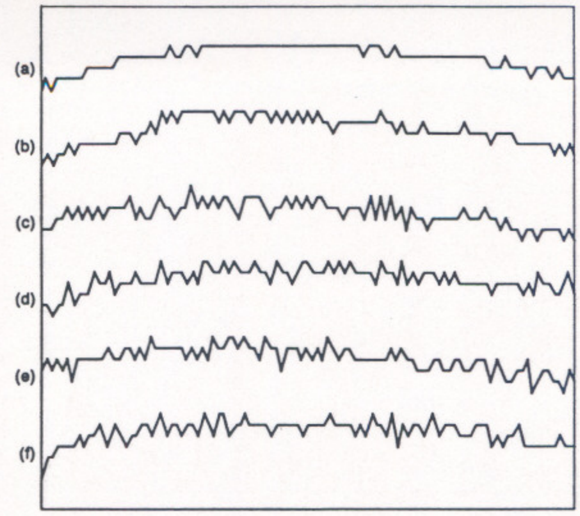

Figure 2. Records of the peaks of six impulses generated at the same charging voltage showing variations in the number of occurences of the maximum value for approximately the same peak value.

The variation of the occurrences of the maximum value makes it difficult to determine the time to peak. One proposed approach is to take the mean value of the time of the first occurrence and the time of the last occurrence of the maximum value to give the time to peak [14]. This approach reduces but does not eliminate the randomizing effect of noise.

The times t_{30}, t_{90} and t_{50} are usually determined by linear interpolation between samples which occur just below and above the relevant level (for example, in [5,6 and 14]). One worker has used local linearization where seven samples (two below and five above the relevant level) are fitted to a straight line using the method of least squares [11].

Even for smooth impulses there may be an overshoot and the evaluation of this overshoot requires an estimate of the impulse without overshoot. One way to automate this determination is to extrapolate the tail of the wave through the region of the overshoot treating the decay as having a single time constant [14]. This approach will give a low estimate of the overshoot but is readily automated.

When there are oscillations on the impulse, it is necessary to generate a smooth impulse from the raw data for analysis. The approach generally used is to apply digital filtering with the simplest approach being to use an unweighted running average. Filtered records for n = 24 and 58 are shown in Figure 3 together with the unfiltered curve (n = 0). The curve with n = 24 is a good approximation to the desired mean curve but still has some oscillations. The curve with n = 58 has no visible oscillations but its front time is obviously significantly longer than that of the recorded impulse. This illustrates the basic problem with filtering but it should be noted that more sophisticated techniques can give better results particularly when the oscillations are not so pronounced [5]. However digital filtering will always cause some degradation of the front time and hence is not universally applicable as this degradation will sometimes lead to unacceptable values.

The curve fitting approach using multiple linear regression has the advantage of using a model based on the circuit used to generate the impulse but suffers from the disadvantage that the decay constants have to be found independently [4]. This paper seeks to extend this approach by applying non-linear regression to the basic model and also by including some additional elements in the model.

MODELS

A simplified circuit of the basic elements needed to generate a high voltage impulse is shown in Figure 4. The generator capacitor C_1 is pre-charged and then isolated from the dc source. The impulse is generated by closing switch G. If the closing of the switch is taken as instantaneous and parasitic components are ignored, the circuit will generate an impulse of which the time dependence is given by a double expontential (DEXP):

$$y(t) = A\{\exp(-at) - \exp(-bt)\} \tag{1}$$

Only the shape of the impulse waveform is of interest for this work. However, the derivation of the constants in equation (1) in terms of the circuit values can be found in the literature [15,16]. The recorded impulse will have been modified by the measuring system and the most obvious effect will be at the start of the impulse which will normally be concave up rather than concave down as occurs for the double exponential of equation (1). This effect can be modelled by a negative triple exponential (NTEXP):

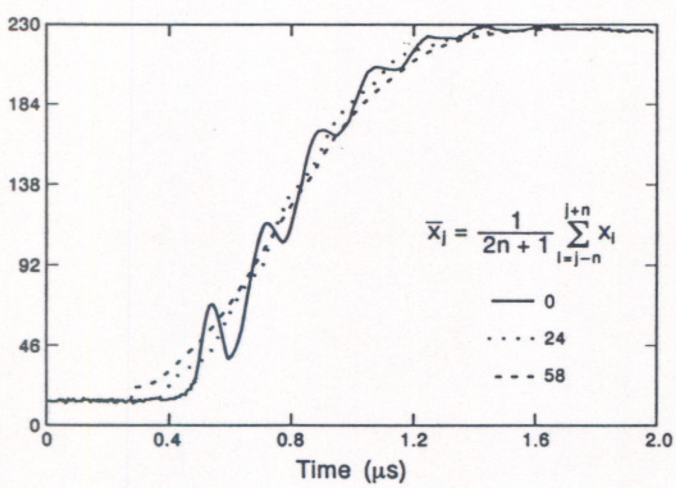

Figure 3. Effects of digital filtering using a "running average" without weighting.

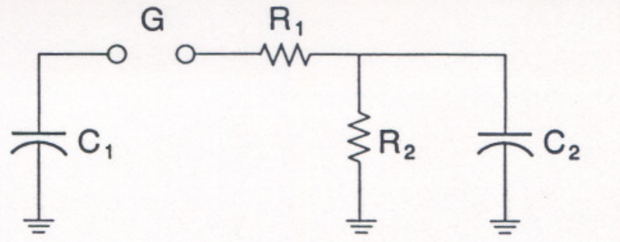

Figure 4. Simplified circuit for the basic model. C_1 generator capacitance, G spark gap, R_1 and R_2 shaping resistors, C_2 load capacitance.

$$y(t) = A\,\{1 - \exp(ct)\}\,\{\exp(-at) - \exp(-bt)\} \tag{2}$$

In addition, from inspection of some of the records fitted during this work, it was decided to model the initial portion by a Gaussian (GEXP):

$$y(t) = A\{1 - \exp(-ct^2)\}\,\{\exp(-at) - \exp(-bt)\} \tag{3}$$

In practical circuits, oscillations can arise from travelling wave effects or from residual inductance in the circuit. Inductance in the circuit may lead to a pronounced overshoot but the amount of this overshoot may be obscured by the oscillations. No attempt is made in this work to model the oscillations directly. However, the mean curve including the overshoot is modelled by a positive triple exponential (PTEXP):

$$y(t) = A\{1 + \exp(-ct)\}\,\{\exp(-at) - \exp(-bt)\} \tag{4}$$

In early versions of the program the start of the impulse and the base magnitude were determined to the nearest time sample and digital level respectively by the operator. Considerable improvement in the fitting was achieved by allowing the program to determine the start of the impulse and allowing interpolation between samples. This was done by replacing t in all the models by $(t - t_1)$ where t_1 is the time offset which is now determined by the program. However, including the amplitude offset as a variable gave some fits which had unreasonably large offsets. For the work reported here the amplitude offset was defined as the mean value before the start of the impulse. A provision to start the curve fitting at an arbitrary point in the record was added by letting the operator select a starting amplitude. This allowed the operator to exclude oscillations at the start of the impulse rather than trying to fit a curve through them.

FITTING METHOD

The general problem of fitting a series of exponentials to a function is an ill-conditioned problem [17] and some specific problems which have been identified are failure to converge, convergence to one of several local minima and sensitivity to starting values of the parameters. This work is restricted to the particular problem of fitting an impulse which is close to a full lightning impulse (front time 1.2 μs, time to half-value 50 μs), starting from parameter values which are close to the expected values and using the models based on functions (1) through (4).

Given data points (t_i, x_i) for i = 1, ..., M, we consider the problem of fitting a model $y(t;\mathbf{p})$ to the data where $\mathbf{p}$ is a vector of unknown parameters. The problem is to compute estimates of those parameters which minimize the quantity Q over a feasible region where Q is given by:

$$Q = \sum_{i=1}^{M} \{x_i - y(t_i, \mathbf{p})\}^2 \tag{5}$$

For the models considered here, this region is defined by the restriction that all parameters are positive. The algorithm employed to estimate the optimal values of the parameters is a modification of the Levenberg-Marquardt algorithm.

The Levenberg-Marquardt algorithm is an iterative search procedure for finding the minimum value of the sum of squares of M nonlinear functions in N variables. It is essentially a combination of the Gauss-Newton and steepest descent methods, and is designed to avoid both the divergence problems associated with the Gauss-Newton algorithm and also the progressively slower convergence frequently encountered in the steepest descent method. The starting point in the search is determined by initial estimates of the optimal parameters. A new search direction is chosen by a suitable interpolation between the search directions provided by the two algorithms. At points where the objective function is rapidly changing (usually these are far from the optimal solution), the search direction is close to that provided by the method of steepest descent. Near the optimal solution, where the gradient of the objective function is small and the function is approximately linear, the search direction is close to that provided by the Gauss-Newton method.

Another feature of the Levenberg-Marquardt algorithm, as implemented in the public-domain software package employed in our study [18], is the use of implicitly scaled variables in order to achieve scale invariance of the method and to limit the size of the correction in any direction where the objective function is changing rapidly. Under reasonable conditions on the objective function, this optimal choice of the correction enhances global convergence from starting points far from the solution and a fast rate of convergence for problems with small residuals.

Earlier work on a double exponential model using particular versions of the Gauss-Newton, Levenberg-Marquardt and the Simplex algorithms [9] provided evidence of the feasibility of this approach and some of the strategy used in this work. This early work demonstrated the sensitivity of the fit to the selection of zero time for the model. In addition, because no attempt was made to model the initial part of the impulse, provision was made to start the curve-fitting at an arbitrary amplitude selected by the operator so that the distorted initial part of the curve could be excluded. The Simplex algorithm was the most robust of these early programs but was too slow to be considered for routine application. The other algorithms were not sufficiently robust and frequently failed to converge. The algorithm used for the detailed results reported in this paper is much more robust and converged for all the data evaluated.

APPLICATION AND EVALUATION

The program allows the operator to select which model is to be used, the length of the record to be used, the amplitude of the record at which fitting is started and the initial value of c (when applicable). The program calculates the fit and plots the raw data together with the fitted curve and the difference between them using Volksgrapher [19]. Volksgrapher has a zoom facility and both the original plot and zoomed plots can be saved to disk, printed or plotted. For convenience in comparing different records all impulses presented in this paper have been zero-referenced by subtracting the initial amplitude offset and then scaled by dividing each value in the record by the zero-referenced maximum value to give a record ranging from zero to one. Hence the peak value of measured impulses will usually be slightly less than one.

Simulated Data

The performance of the program was evaluated using a calculated 1.2/50 impulse and the same impulse contaminated with noise (1% peak-to-peak). The impulse was calculated for a record length of 1500 samples using two sample rates so that the first 10 μs were calculated at higher time resolution and the succeeding 50 μs at lower resolution. This corresponds to the usual method of recording high voltage impulses. The parameter values of this calculated impulse are given in the top row of Table 1. The parameter values for the impulses calculated from each model using the pre-set initial estimates of the exponents and time offset for that model are given in rows two to five of Table 1. These pre-set initial estimates were selected to give initial waveforms which are sufficiently close to the measured waveforms.

Table 1. Initial Values

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak Value
Input	1202	2311	50 220	1.0
DEXP	1141	2066	30 195	0.945
NTEXP	1101	1974	30 094	0.9456
PTEXP	981	1923	30 051	0.9445
GEXP	1002	2049	30 192	0.945

Each of the models was fitted to the calculated impulse and the results are given in Table 2. The parameter values of the calculated impulse are given in the top row. The results of fitting the data by the four models are given in rows two to five as errors with respect to the correct values given in the top row. For comparison, the values found by a commercial program using the histogram approach (HIST [20], row six) combined with some smoothing and interpolation and by using the mean value are shown. MEAN1 (row seven) calculates the peak value as the mean value of the interval defined by the first and last occurrences of the maximum value and MEAN2 (row eight) calculates the peak value as the mean value of the interval defined

Table 2. Input values and errors in the parameter values found by fitting each model to a 1.2/50 impulse with no noise

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak value (ppm)
Input	1202	2311	50 220	10^6
DEXP	0	−1	+1	2
NTEXP	0	0	+1	−0.4
PTEXP	0	0	+1	0
GEXP	0	0	+1	−0.5
HIST	+5	NA	+7	0
MEAN1	0	0	−2	0
MEAN2	−2	0	−1	−14

NA = Not applicable

by the first and last occurrences of the level below the maximum value. The 30%, 90% and 50% points are found using linear interpolation between samples of the raw data file.

The values obtained using the double exponential model provide a measure of the accuracy of the program. The values obtained using the other models show how well the program can suppress the additional term when there is no component in the input which corresponds to it. The displayed resolution of the computer for the calculated peak value is 0.1 ppm (part per million) while all time parameter values are rounded to the nearest nanosecond. For impulses with no noise and files of length 1500 words, the calculated peak values are all within 2 ppm while the calculated time parameters are within 1 ns. HIST, MEAN1 and MEAN2 all give high accuracies for the smooth calculated impulse.

Ten different files were created from the calculated impulse by adding noise of 1% peak-to-peak amplitude. Each of the models were fitted to these files and the mean values of the errors, followed by their standard deviations in parentheses, are given in rows two to five of Table 3. Examples for single files are given for HIST, MEAN1 and MEAN2.

Table 3. Input values and errors in the parameter values calculated by each model for the calculated 1.2/50 impulse with added noise

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak value (ppm)
Input	1202	2311	50 220	10^6
DEXP	0(4)	−1(7)	−36(75)	−78(219)
NTEXP	3(5)	9(16)	10(56)	−42(239)
PTEXP	1(4)	1(7)	8(54)	29(107)
GEXP	6(5)	78(89)	32(72)	−971(1335)
HIST	−48	NA	−434	−7500
MEAN1	−32	+139	+429	−3400
MEAN2	−32	+139	+429	−3400

Considering a range of the mean value plus/minus twice the standard deviation, it can be seen that DEXP gives peak values within 0.05% and time parameters within 1%. NTEXP and PTEXP give values which are nearly as good while GEXP gives larger errors. The precision required from comparative measurements in the relevant Draft International Standard for comparative measurements is 1% for peak voltage and 5% for time parameters. Applying a margin of a factor of ten gives target values of 0.1% for peak voltage and 0.5% for time parameters. The mean values are well within these limits for a calculated 1.2/50 impulse with added noise of which the peak-to-peak amplitude is 1%. Values obtained from HIST and MEAN1 (the peak value found by MEAN2 happened to be the same as that for MEAN1 and hence all the time values will be identical as well) had larger errors but were well within the limits required by the Standard.

Tests using high voltage impulses

Tests were performed using the usual impulse circuits in two different laboratories. In laboratory A, the circuit components had extremely low residual inductance leading to a high rate of rise of the voltage on the Marx generator which led to travelling wave oscillations. These oscillations are normally damped fairly rapidly (Group A1) but for this work some impulses were taken with some of the internal damping resistors shorted to give more pronounced oscillations but with a shorter front time than is allowed by the standard tolerances (Group A2). In laboratory B, a commercially-supplied Marx generator was used and the residual inductance was higher. This provided a "smooth" impulse (Group B1). Some internal resistors were shorted to provide impulses with pronounced oscillations (Group B2). However, additional capacitance was added to give a front time which is slightly higher than is allowed by the standard tolerances. Two criteria were used to judge how well the programs provided the desired smooth impulse. The first was a value judgement made on a high resolution plot of the recorded data overlaid with the fitted curve and the second was the root mean square (rms) value of the residuals.

Group B1 — "Smooth" Impulses: The impulses in group B1 are sufficiently smooth to be classed as "smooth" impulses and indeed appear to be so when recorded on an oscillogram. However, when recorded on a high resolution digitizer and displayed on a high resolution screen, small oscillations can be observed. The form of these becomes clearer when the recorded impulse is overlaid with a fitted curve. An example is given in Figure 5. The B1 impulses were recorded on a 10 bit digitizer at 10 ns/sample for 1400 words followed by 100 ns/sample for 648 words to give a record length of nearly 80 μs. Impulses were generated with various front times and times to half-value. An example of the analysis of a short front time combined with a long time to half-value impulse is given in Table 4.

The record (see Figure 5) has a small foot before the rapid rise portion. Neither NTEXP nor GEXP is able to fit this portion of the curve but GEXP is more affected by it and this leads to poorer values of the parameters. Other than this initial portion DEXP, NTEXP and PTEXP all give an apparently good fit judging from the plotted curves and the rms value of the residuals (the rms values of the residuals in parts per thousand are 3, 3, 5 and 3 for DEXP, NTEXP, PTEXP and GEXP, respectively). In this case, where the oscillations are small, there is not sufficient evidence to pick one of the three models as best. HIST, MEAN1 and MEAN2 give comparable values for the peak value, the front time and the time to half-value but the values of the time to peak are quite low. It should also be noted that in this

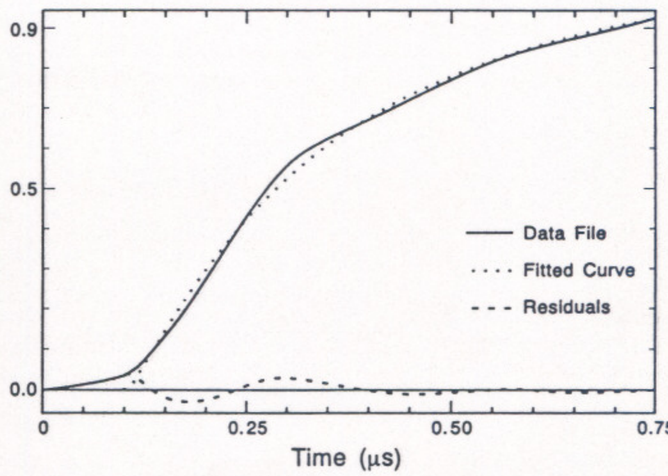

Figure 5. The first 750 ns of a Group B1 impulse showing the fitted DEXP curve and the small amplitude oscillations on the recorded data. The difference between these curves (residuals) is shown on the same scale.

Table 4. An Impulse from Group B1
Parameter Values found by each model

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak Value
DEXP	814	1683	59 487	0.9978
NTEXP	818	1722	59 506	0.9974
PTEXP	826	1663	59 468	0.9983
GEXP	841	1797	59 532	0.9967
HIST	811	NA	59 567	0.9990
MEAN1	819	1515	59 288	0.9995
MEAN2	818	1570	59 292	0.9993

example the form of the oscillations is such that t_{30} and t_{90} will both be estimated low by HIST, MEAN1 and MEAN2 leading to partial cancellation of the errors.

Group A1 — Impulses with damped travelling-wave oscillations: The front of an impulse from this group is shown in Figure 6 and the results of the analysis of this impulse are given in Table 5. This impulse was recorded on a 8 bit digitizer at 5 ns/sample for the first 1200 samples and then at 100 ns/sample for the next 848 samples. DEXP and PTEXP did not give a good fit over the first part of the impulse. NTEXP gave a reasonable fit and GEXP gave a good fit. This subjective evaluation was supported by the rms values of the residuals (the rms values of the residuals in parts per thousand are 20, 14, 19 and 13 for DEXP, NTEXP, PTEXP and GEXP, respectively). When compared with GEXP, the programs HIST, MEAN1 and MEAN2 did well on the estimation of peak value but only HIST gave a good value of the front time.

Table 5. An Impulse from Group A1
Parameter values found by each model

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak Value
DEXP	1498	2689	36852	0.9998
NTEXP	1367	2382	36798	0.9993
PTEXP	1488	2669	36850	0.9997
GEXP	1264	2508	36952	0.9956
HIST	1279	NA	36904	0.9948
MEAN1	1412	2350	37028	0.9957
MEAN2	1392	2420	37046	0.9940

Group B2 — Impulses with pronounced oscillations from residual circuit inductance: The front of an impulse from this group is shown in Figure 7 and the results of the analysis given in Table 6. This impulse was recorded on a 10 bit digitizer at 10 ns/sample for the first 1296 samples and then at 100 ns/sample for the next 752 samples. Again, neither DEXP nor PTEXP gave a good fit over the first part of the impulse: the best fit

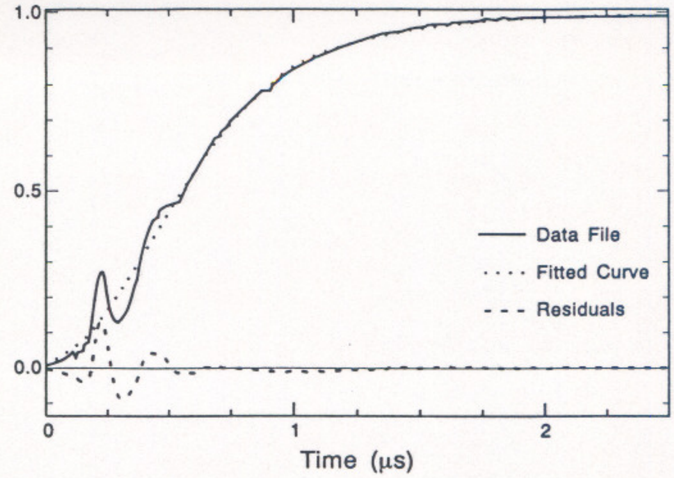

Figure 6. The first 2.4 μs of a Group A1 impulse showing the fitted GEXP curve together with the recorded data and the residuals.

Table 6. An impulse from Group B2
Parameter values found by each model

Model	Front time (ns)	Time to peak (ns)	Time to half-value (ns)	Peak Value
DEXP	1703	3218	62022	0.9939
NTEXP	1602	3071	62007	0.9942
PTEXP	1696	3204	62016	0.9940
GEXP	1556	3302	62168	0.9911
HIST	1622	NA	62186	0.9945
MEAN1	1620	2915	61409	0.9972
MEAN2	1620	2940	61407	0.9973

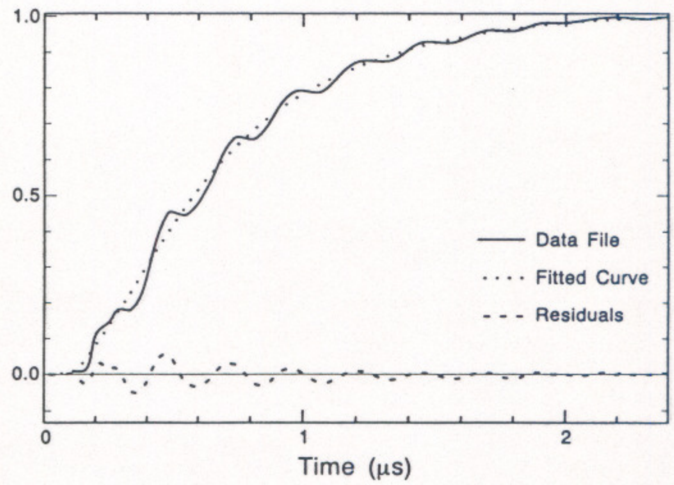

Figure 7. The first 2.4 μs of a Group B2 impulse showing the fitted NTEXP curve together with the recorded data and the recorded data and the residuals.

was provided by NTEXP. As before the subjective evaluation of the performance of the fitting programs is supported by the rms value of the residuals (the rms values of the residuals in parts per thousand are 7, 6, 7 and 8 for DEXP, NTEXP, PTEXP and GEXP, respectively). When compared with NTEXP, both MEAN1 and MEAN2 gave high estimates of the peak value while GEXP gave the lowest estimate. Again HIST performed well but does not provide an estimate of the time to peak.

Group A2 — Impulses with pronounced travelling-wave oscillations: The front of an impulse from this group is shown in Figure 8 and the results of the analysis of this impulse are given in Table 7. This impulse was recorded on an 8 bit digitizer at 5 ns/sample with 1000 samples per record so only the first 5 μs was recorded. To obtain these pronounced oscillations it was necessary to use a front time considerably faster than the lower limit (840 ns) for a standard lightning impulse. GEXP gave the best fit. Although DEXP and NTEXP gave the same peak value as GEXP, the front times were longer(the rms values of the residuals in parts per thousand are 28, 23, 26 and 19 for DEXP, NTEXP, PTEXP and GEXP, respectively). MEAN1 and MEAN2 gave high peak values and front times, while HIST gave low values.

Table 7. An impulse from Group A2
Parameter values found by each model

Model	Front time (ns)	Time to peak (ns)	Peak Value
DEXP	463	917	0.9856
NTEXP	423	814	0.9856
PTEXP	480	819	0.9992
GEXP	378	626	0.9857
HIST	303	NA	0.9227
MEAN1	417	555	1.0000
MEAN2	417	550	0.9992

Basis for the definition of waveform parameters

The authors propose that waveform parameters should be re-defined and should be based on a fitted curve rather than the raw data. This will increase the precision with which the parameters can be determined and will reduce the effects of noise and any local abberrations. This increase in precision will be useful both in making more accurate comparative measurements to qualify an industrial measuring system against a reference measuring system and in research on problems in high voltage systems. However, as yet very few measurements have been made using precision much higher than required by the present standards and it is not possible to infer the effects that this increased precision will have on high voltage practice and design.

The authors suggest that one of the following approaches be used:

1. Define the waveform parameters in terms of a fitted double-expontential curve. In addition, limits would be placed on the size and form of the residuals.

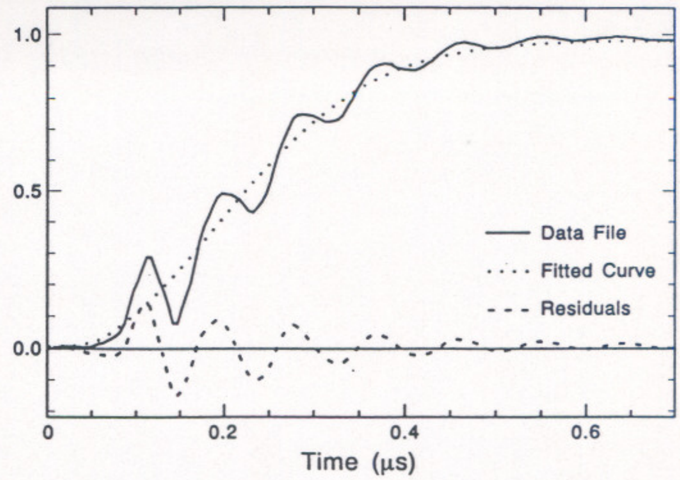

Figure 8. The first 700 ns of a Group A2 impulse showing the fitted GEXP curve together with the recorded data and the residuals.

2. Allow the user to pick the most suitable curve from a family defined by the standard. This family could include the four models studied here plus any additional models found to be needed in other laboratories. Again, limits would be placed on the size and form of the residuals.

3. Use a double-exponential curve but allow fitting to start at a fixed amplitude (for example, 50%), which would allow any initial distortions to be ignored. Limits could be set on both the initial part of the curve and on the size and form of the residuals. This approach gives shorter front times and times to peak than the present practice but amplitudes and times to half-value agree well with the best values determined in this work. This approach is consistant with the fact that the lower part of the impulse has little practical effect on the insulation.

4. Some combination of proposals 1 to 3 could be used.

It is too early to attempt to decide on which of the above proposals should be adopted. It is necessary to expand the data base to include impulses taken under a variety of conditions in different test laboratories. Work on such an expanded data base may lead to new proposals.

CONCLUSIONS AND FUTURE WORK

Curve-fitting routines based on four models and three other programs have been evaluated using a calculated full lightning impulse and the same impulse contaminated by 1% noise. All programs returned parameter values which were within the requirements of present standards for industrial measurements and within proposed limits for comparative measurements using a reference measuring system to qualify an industrial measuring system. However, when applied to impulses contaminated by noise, the curve-fitting routines returned parameter values which were much more accurate than those returned by the other programs. The same routines have been applied to records of high voltage impulses from four different circuits. All programs perform well for "smooth" impulses but particular curve-fitting routines perform best for impulses with superimposed oscillations. GEXP performed best with impulses in groups A1 and A2 while NTEXP performed best with impulses in group B2.

The differences observed in impulses from laboratories A and B suggests that a more widely-based evaluation should be made.

A joint study organized by the IEEE Working Group on Digital Signal Processing (Chairman: T.R. McComb), the IEC Technical Committee 42 Working Group 8 (Convenor: Dr. R. Malewski) and CIGRE Working Group 33.03, High Voltage Testing Techniques (Convenor: Prof. K. Feser) has been initiated. This new study will establish a data base from many laboratories. This data base will be circulated so that each participating laboratory can evaluate their own software on the entire data base. The results of the joint study will be incorporated into the relevant standards and can be expected to lead to more appropriate definitions of impulse parameters.

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BIOGRAPHIES

Terence R. McComb (M'76–SM'83) was born in Belfast, Northern Ireland, on October 5, 1944. He received the B.Sc. and the Ph.D. degrees in physics from the Queen's University of Belfast, Northern Ireland, in 1968 and 1974 respectively.

From 1974 to 1976, he worked at the University of Western Ontario, London, Ont., Canada, studying ion-molecule reactions. Since 1976, he has worked in the Power Engineering Group at the National Research Council of Canada, Ottawa, Ont., Canada. His current research interests include impulse measuring systems and the use of digital equipment in high-voltage laboratories.

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John E. Lagnese received the Ph.D. degree in mathematics from the University of Maryland in 1963.

After spending one year as a National Academy of Sciences-Material Research Council Post-doctoral fellow at the National Bureau of Standards, he joined the faculty of Georgetown University where he served as Chairman of Mathematics from 1971 to 1983 and where he is presently a Professor of Mathematics. During 1983-1985 he was Program Director of the Applied Mathematics Program at the National Science Foundation. He joined the Applied Electrical Measurements group of the National Bureau of Standards in 1982 on a part-time basis. His work has dealt primarily with mathematical issues connected with stabilization and control of flexible stuctures, and with measurements of high voltage transients.