Voltage linearity of scale factor and wave shape parameters of UHV impulse voltage dividers

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SUMMARY

Determining the voltage linearity of a large impulse voltage divider used in the testing of ultra-high-voltage (UHV) equipment is a challenging task. This leads to the question of whether the uncertainty requirements, specified in the present edition of IEC60060 [1, 2], can be met in the UHV range. This paper presents the results of voltage divider linearity tests at voltages up to 2400 kV. Measurements of the voltage linearity of the divider scale factor (or peak voltage), as well as the voltage linearity of the time parameters, are presented. Methods for calculating the linearity values and their interpretation are discussed. It is concluded that achieving voltage linearity of less than 3% for scale factor and voltage linearity of less than 5% for time parameters may be difficult for dividers used for testing in the UHV range. Other voltage linearity methods should be studied in order to appropriately specify measurement uncertainties for impulse testing in the UHV range.

KEYWORDS

Impulse voltage, voltage divider, voltage linearity, UHV testing.

INTRODUCTION

The voltage rating of reference impulse voltage dividers is usually insufficient for calibrating impulse dividers over their full operating voltage range. This is especially true when calibrating dividers used for testing UHV equipment. In such cases, a voltage linearity test of the voltage scale factor of the divider can be performed, over the full operating range as recommended in IEC 60060-2[2]. The linearity test aims to prove that the scale factor, determined by calibration against a reference divider at a lower voltage, is valid within the specified measurement uncertainty over the entire operating range. However, the present edition of IEC 60060-2, which specifies measurement uncertainty of less than 3% for the peak voltage, does not include measurement systems used for testing in the UHV range. There is not sufficient experimental evidence to show that the present linearity test method can be used for approving measurement systems for voltages above currently standardised levels, should the specified measurement uncertainty limit for peak voltage remain at 3%.

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A commonly used method for proving the voltage linearity of the scale factor is to compare the peak voltage reading of the impulse divider under test with the DC charging voltage of an impulse generator. However, experience has shown that this method presents additional difficulties when the operating range is extended to the UHV range. These difficulties include heating of the generator components associated with high charging voltages, long charging times and the onset of corona discharge in the generation and measurement circuit. An alternative method, using a field probe, is also prone to the effects of corona. This paper discusses measurement results obtained with the charging-voltage method on dividers with voltage ratings up to 2800 kV. Linearity tests using field probes are not discussed in this paper.

Another relevant issue that has not been specifically addressed in IEC 60060-2 is the voltage linearity of the wave shape parameters (called time parameters in the IEC standards). The wave shape parameters can be affected by the frequency response of the divider, which is normally assessed with a low voltage step response measurement. However, the frequency response of the divider may change at a higher voltage when corona starts to appear on the surface the divider. The onset of corona changes the stray capacitance of the high-voltage arm, which may in turn change the frequency response of the divider. Changes in the wave shape parameters up to 10% have been observed during voltage linearity tests. Whether the changes are caused by changes in the generated waveforms or by change of the frequency response of the divider are difficult to distinguish by experiment. It is therefore not presently known if the time parameter uncertainty limit of 10% can be met in the UHV range.

The relevant IEC technical committee is in the process of drafting an amendment to IEC60060 to specify the requirements for high-voltage testing of UHV equipment. Under review is the requirement of measurement uncertainties for impulse measurement systems. Experimental results presented in this paper will be useful in the revision of IEC60060.

TEST ARRANGEMENTS

Two divider/generator combinations are discussed in this paper:

1. The peak voltage reading of a 2800 kV divider was compared with the first stage DC charging voltage of a 15-stage, 3000 kV/300 kJ, impulse generator. The divider was a damped capacitor type. A photograph of the 2800 kV divider is shown in Figure 1.

2. The peak voltage reading of a 2400 kV divider was compared with the first stage DC charging voltage of a 14-stage, 2800 kV/28 kJ, impulse generator. The 2400 kV divider was also a damped capacitor type. A photograph of the 2400 kV divider is shown in Figure 2.
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DEFINITION AND USE OF VOLTAGE LINEARITY

As described in IEC 60060-2, the linearity test is specified to extend the value of the scale factor from the maximum voltage at which the calibration has been performed to the upper limit of the assigned measurement range. The linearity test is a practical solution to the problem that voltage ranges of reference measurement systems are normally much lower than the voltage ranges of dividers used for high-voltage tests. The maximum operating voltage of reference measurement systems commonly used today is between 200 kV and 1000 kV, while the lightning impulse test level for equipment used in 1000 kV AC transmission systems is usually 2400 kV.

It is possible to define and calculate voltage linearity by several methods, leading to differing results.

In the present edition of IEC 60060-2 [2], the voltage linearity of the scale factor is calculated from the ratio between the peak voltage reading of the impulse measurements system and another suitable voltage in the impulse test system, such as the generator first stage DC charging voltage, or alternately the voltage output of an electric field sensor.

Thus

\[ R_i = \frac{V_{pi}}{V_{ci}} \quad (i=1,2,...,n) \]

where

- \( R_i \) is the linearity ratio,
- \( V_{pi} \) is the peak voltage reading of the impulse divider,
- \( V_{ci} \) is the DC charging voltage of the impulse generator and
- \( n \) is the number of test voltage levels.

The voltage non-linearity of the scale factor is then determined as:

\[
\Delta R_{\text{max}} = \max_{i=1}^{n} |\Delta R_i| \\
= \max_{i=1}^{n} \left|100 \times \frac{R_i - R_m}{R_m}\right|
\]

(1)

where \( \Delta R_{\text{max}} \) is the maximum of individual ratio deviations \( \Delta R_i \) and \( R_m \) is the average of ratio values \( R_i \) at \( n \) voltages.

According to IEC 60060-2, the value \( \Delta R_{\text{max}} \) so determined shall be used as a measurement uncertainty component in calculating the combined measurement uncertainty of the impulse measurement system.

In this paper, two other methods of calculating \( \Delta R_i \) are discussed.

Firstly, defining the first linearity ratio, \( R_1 \), as the ratio at the lowest test voltage level \( i=1 \), and replacing \( R_m \) with \( R_1 \) gives:

\[
\Delta R_{\text{max}} = \max_{i=1}^{n} |\Delta R_i| \\
= \max_{i=1}^{n} \left|100 \times \frac{R_i - R_1}{R_1}\right|
\]

(2)

Thus the ratio deviations are calculated with reference to the first linearity ratio \( R_1 \).
Secondly, $\Delta R_i$ is calculated as a deviation from a regression line:

$$\Delta R_{\text{max}} = \max_{i=1}^{n} |\Delta R_i|$$

$$= \max_{i=1}^{n} \left| 100 \times \frac{V_{pi} - V_{gi}}{V_{gi}} \right|$$

(3)

where $V_{pi}$ are the peak voltage readings at voltage levels $i=1, \ldots, n$,
$V_{gi}$ is the voltage value corresponding to charging voltage reading $V_{ci}$ on the line
obtained by a linear regression calculation using all values of $V_{pi}$ and $V_{ci}$.

This paper also presents measured time parameter deviations as a function of the test voltage. A time parameter deviation is calculated as the percentage difference of the time parameter at a particular voltage level to that at the lowest voltage level.

RESULTS OF SCALE FACTOR LINEARITY AND DISCUSSION

Figures 3 and 4 show the test results for the 2800 kV divider. Each $V_c$ value is the average of 4 nominally equal charging voltages and each $V_p$ value the average peak voltage of the corresponding impulses.

Figure 3 shows that the measured maximum ratio deviation, $\Delta R_{\text{max}}$, or the voltage non-linearity of the peak voltage, was 2.0 %. The value was obtained using the calculation method in the present IEC 60060-2. The line in Figure 3 is drawn with a gradient equal to $R_m$ and zero $V_p$ intercept. It can be seen that the relationship between $V_p$ and $V_c$ appears to be curved. The curve becomes more apparent when a line is drawn with a gradient equal to $R_1$ (the linearity ratio at the lowest voltage) as shown in Figure 4, in which the non-linearity value now becomes 3.4 %.

Figure 3 Voltage linearity test of the 2800 kV divider with positive lightning impulse, with gradient of the line being the average ratio $R_m$ (IEC method)

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The higher $\Delta R_{\text{max}}$ value may not necessarily be the result of a non-linear behaviour of the voltage divider. Very often it is the result of the non-linear relationship between the charging voltage reading and the output voltage of the impulse generator. The influence of the generator normally becomes more pronounced when the generator charging voltage is close to the upper limit of its range. The higher $\Delta R_{\text{max}}$ value in this test could be indeed due to the generator related factors. However, it is also possible that the non-linear curve was due to the true non-linearity of the divider. If this was the case, the $\Delta R_{\text{max}}$ value of 2% (Figure 3) would be an under-estimate of the non-linearity. The IEC method would then fail to disqualify this divider. The $\Delta R_{\text{max}}$ value with reference to $R_1$ (Figure 4) would be a more accurate estimate of the voltage non-linearity, which would lead to the disqualification of the divider.

Figure 5 shows the values of the ratio deviation obtained using $R_m$ as the reference and those using $R_1$ as the reference. It can be seen that there is a shift between the deviation values obtained by the two methods, with the values based on $R_m$ always giving a lower $\Delta R_{\text{max}}$.

Figure 6 shows the results for the same divider with negative impulses. The deviation values at the higher voltages were much lower than those obtained with positive impulses. The difference between the results for the two polarities indicates that corona discharge was the most likely factor that caused the measured deviations. However, it is not clear if the deviation was due to the change of the generator efficiency as a result of the corona or due to the change of stray capacitance in the divider high-voltage arm caused by corona. The latter would change the ratio of the divider and hence cause a real non-linear response to the input voltage. In the absence of any other evidence, it is not possible to conclude if the measured deviations were due to a true non-linear response of the divider.
Figure 5 Ratio deviations calculated from two different linearity ratios, result for positive impulse voltage

Figure 6 Ratio deviations calculated from two different linearity ratios, result for negative impulse voltage
Figures 7 and 8 show the test results of the 2400 kV divider at test voltages up to ±1400 kV.

It can be seen from Figure 7 that the absolute deviation values $\Delta R_i$ were less than 1%, irrespective of the calculation method used. It is believed that the scatter of the results can be attributed to the measurement uncertainties of the peak voltage and the DC charging voltages, and the fluctuation of the impulse generator efficiency. This result shows that if the deviations are random and low, the present IEC method would work well.

However, the results with negative impulses (Figure 8) show that there was a trend of increasing negative ratio deviation. The maximum ratio $\Delta R_{max}$ was close to 5% when ratio $R_1$ (ratio at the lowest test voltage) was used as the calculation reference. It is not conceivable that the divider response could be non-linear with negative impulses, while being linear with positive impulses. If there were any effect from corona, the effect of positive impulse would be more significant than that of the negative impulse. This is because the corona inception voltage of positive impulses would be lower than that of negative impulses.

To study the cause for the non-linear results at negative polarity, the test data are presented in Figure 9 in the form of a relationship between $V_p$ and $V_c$. Two lines are fitted to the same data. The dotted line is calculated according to the IEC method, i.e., using the average ratio $R_m$ as its gradient. This line does not appear to be a good fit to the test data. The solid line is fitted using linear regression calculation but without restricting the intercepts. The deviation values $\Delta R_i$ (using Eq. 3) from the regression lines are also shown in Figure 8 (as red circles). It can be seen from Figures 8 and 9 that the regression line fits the test data well. There is no evidence of a non-linear relationship.

However, the intercept of the regression line at the $V_p$ axis is not zero, which indicates that there was an offset in either the reading of the peak voltage or the reading of the DC charging voltage. Comparison with the test data of the positive polarity indicates that there was indeed a systematic offset in the negative charging voltage reading.

![Figure 7 Ratio deviations calculated from two different linearity ratios, result for positive impulses](image-url)
Figure 8 Ratio deviations calculated from three different linearity ratios, result for negative impulses

Figure 9 Results of negative impulses fitted by linear regression calculation and by the line with gradient of the average linearity ratio $R_m$

The example of the 2400 kV divider shows that when there is an offset in the charging voltage indication, the IEC method, using the average linearity ratio $R_m$, significantly overestimates the non-linearity value $\Delta R_{max}$. In such cases, the method using a regression line would be acceptable if it can be established that the offset is not from the impulse divider and the digital recorder of the measuring system.
RESULTS OF TIME PARAMETER LINEARITY MEASUREMENT AND DISCUSSION

Figure 10 shows the measured deviation of time parameters of the 2400 kV divider with negative impulses. The highest test voltage was -1450 kV, which was significantly lower than the rated voltage of the divider (2400 kV) and the rated voltage of the generator (2800 kV). The results show that the deviations were much lower than the measurement uncertainty of 10% required for time parameters. The results in Figure 10 would be typical for tests in the voltage range well below the rated voltage (divider and generator), where there would normally be no significant corona and the values of the generator elements (resistors and capacitors) would normally remain stable.

Deviations of time parameters would typically increase when the peak voltage approaches the rated voltage of the test system. Figure 11 shows the deviations at voltages up to 2400 kV for the 2800 kV divider at positive polarity. It can be seen that deviations of both \( T_1 \) and \( T_2 \) were approaching their uncertainty limit of 10%. The deviations at negative polarity (Figure 12) were lower and high deviations at negative polarity also started at higher voltages. The difference between the results for the two polarities indicates that deviation was also likely caused by corona. It is however not clear if the corona caused a change in the generated waveform or a change of the capacitance of the divider high-voltage arm which resulted in waveform distortion by the divider. As discussed in [3], time parameters \( T_1 \) and \( T_2 \) are very sensitive to waveform distortion. Either waveform change caused by the generation circuit or distortion by the divider would cause the observable time parameter deviations. It was therefore not possible to determine if the time parameter deviations was due to waveform distortion by the divider.

The large deviations of the time parameters at the higher voltage levels show that it may be necessary to measure voltage linearity of the time parameters for dividers used in UHV testing. An alternative approach is to increase the uncertainty limit of time parameter measurements.
Figure 11 Deviation of the time parameters from their values at the lowest test voltage, 2800 kV divider and impulse of positive polarity.

Figure 12 Deviation of the time parameters from their values at the lowest test voltage, 2800 kV divider and impulse of negative polarity.
CONCLUSION

Linearity tests discussed in this paper show that the method in the present 60060-2 may underestimate the true voltage non-linearity of an impulse divider. It was found that obtaining a sufficiently low voltage linearity value to qualify dividers for testing in the UHV range can be challenging. Therefore, the risk of exceeding the uncertainty limit of 3% for test voltage in the UHV range is significant when the present IEC method for estimating the voltage non-linearity is used. A better estimate is to use the linearity ratio determined at the calibration voltage (normally the lowest voltage for linearity test) as the reference for estimating the maximum non-linearity value.

It was also found that the verification of the voltage linearity of time parameters to be within the uncertainty requirement of 10% was also challenging in the UHV range. It is recommended that the extension of IEC 60060 for UHV testing should consider the possible effects of voltage on the measurement uncertainty of the time parameters.

BIBLIOGRAPHY