Abstract—This paper describes about the design, testing and practical applications of two types of high order FIR digital filters viz. Kaiser filter and Equi-ripple filter for noise reduction and data smoothing of high voltage impulse waveforms. In this work, the raw data were smoothened depending on the noise in the time domain and the peak values were evaluated. Double exponential mean curves were drawn and overshoot was evaluated by using Double exponential curve fitting method.

Index Terms— Lightning Impulses, FIR filters, low-pass filter

I. INTRODUCTION

Traveling waves of steep wave front follows transient disturbances on a transmission system due to lightning strokes and switching operations. These waves cause unequal stress distribution along the windings of a power transformer, along insulators etc. and may lead to breakdown of the insulation system. It is, therefore necessary to study the insulation behavior under impulse test voltages.

The test stress should be high enough concerning the sensitivity but low enough to prevent an initiation of undetected defects during the test procedure, which may lead to damage after a certain period of service. Hence, before installation of high voltage power apparatus it is required to test their withstand capability against over voltages which can be generated in laboratory using Marx Impulse Generator.

The parameters of Lightning Impulse can be determined as per IEC 60-1 [1] if the measured impulse is smooth. However, difficulties arise if the oscillations or overshoot are superimposed on the waveform.

In such cases standards [1-2] require to draw the mean curve to calculate the amplitude and frequency of the superimposed oscillation / the corresponding duration of overshoot in order to evaluate the test voltage $U_{test}$. Tests with Lightning Impulse voltages are specified in IEC Publication 60060-1 and IEC 61083-2 [4] to demonstrate the response of high voltage power system apparatus to transient over voltages due to natural operating conditions.

The recommended procedure in the standard for determination of the peak value of a standard Lightning Impulse with an overshoot or an oscillation on the peak is ambiguous. The evaluation of an impulse when the application of standard Lightning Impulse results in a non-standard waveform, as in tests on transformers, is not addressed in the standard.

II. STANDARD LIGHTNING IMPULSE

A. Time Parameters

A lightning impulse voltage is a unidirectional voltage which rises rapidly to a maximum value and then decays slowly. Standard lightning impulse according to IEC 60060 is $1.2 \mu s \pm 30\% / 50 \mu s \pm 20\%$. The tolerance allowed in the peak value is $\pm 3\%$.

A lightning wave can be represented as double exponential wave defined by the equation:

$$ V = V_0 \cdot \left[ e^{-\alpha \cdot t} - e^{-\beta \cdot t} \right] $$

where $\alpha$ & $\beta$ are constants of $\mu s$ values.

![Fig. 1 Illustration of the time parameters of a full standard Lightning Impulse](image)

The front or rise time $T_1$ is given by:

$$ T_1 = 1.25 \left( O_1 \times T_{90\%} - O_1 \times T_{50\%} \right) $$

The tail or fall time $T_2$ is given by:

$$ T_2 = O_1 \times T_{50\%} $$

The straight line through the 10% and 90% points on the impulse wave gives the virtual origin point $O_1$.

Sometimes, due to disturbances present in the initial part of the curve, 30% point on the impulse wave is preferable and hence the front time $T_1$ is given by:
\( T_1 = 1.67 \left( O_1 \times T_{90\%} - O_1 \times T_{30\%} \right) \)  

**III. CONSIDERATIONS IN FILTER DESIGN**

There is no standard procedure to determine the overshoot, as different algorithms used to compute mean curve which gives various parameters.

The proposal of using the high order Finite Impulse Response (FIR) filters for the evaluation of the test voltage takes the considerations from the previous attempts [5] that the amplitudes increase very quickly with front times greater than 0.84 \( \mu \)s which contain negligible frequency components above 3 MHz. Hence an attempt is made that low pass filters with a pass-band cut-off frequency around 3 MHz can be used to eliminate noise above this frequency without affecting the main signal. The filter characteristics, however, can never be ideal.

**A. Ideal Low-pass filter**

The ideal low-pass filter is one that allows through all frequency components of a signal below a designated cutoff frequency (\( \omega_c \)), and rejects all frequency components of a signal above \( \omega_c \).

Its frequency response satisfies the following equation,

\[
H_{LP}(e^{j\omega}) = \begin{cases} 
1, & 0 \leq \omega \leq \omega_c \\
0, & \omega_c < \omega \leq \pi
\end{cases} \tag{3.1}
\]

The impulse response of the ideal lowpass filter (3.1) can easily be found to be

\[
h_{LP}[n] = \frac{\sin(\omega_c n)}{\pi n}, \quad -\infty < n < \infty. \tag{3.2}
\]

**B. FIR Low-pass filters**

Use As the impulse response required to implement the ideal low-pass filter is infinitely long, it is impossible to design an ideal FIR low-pass filter.

Finite length approximations to the ideal impulse response lead to the presence of ripples in both the passband (\( \omega < \omega_c \)) and the stopband (\( \omega > \omega_c \)) of the filter, as well as to a nonzero transition width between the passband and stopband of the filter (see Figure 2).

**C. FIR filter design specifications**

Both the passband/stopband ripples and the transition width are undesirable but unavoidable deviations results from the response of an ideal lowpass filter when it is approximating with a finite impulse response. Practical FIR designs typically consist of filters that meet certain design specifications, i.e., that have a transition width and maximum passband/stopband ripples that do not exceed allowable values. In addition, one must select the filter order (\( b \)), or equivalently, the length (\( N \)) of the truncated impulse response.

**D. FIR filter design**

The coefficients of the FIR filter are equivalent to the filter’s impulse response.

The characteristics of ideal lowpass filter with its frequency response are shown in Figure 3 for transition band (\( f_{\Delta} \)). The areas in the figure show the tolerance regions of the actual frequency response to be approximated, and the frequencies \( f_p \) and \( f_s \) represent the passband (\( f_p \)) and stopband (\( f_s \)) edge frequencies respectively. Finally, the frequency range \( f_p > f > f_s \) is referred to as the transition band. Because of the discontinuity at the passband frequencies, these ideal frequency characteristics are not physically realizable.

Therefore, a filter approximation function that approaches the ideal responses within the specified tolerance passband and stopband regions must be found. The approximation problem...
for digital filter design is conceptually no different than that for analog filter design [7]. The digital filter design problem requires the determination of the difference equation coefficients to meet the desired filter characteristics, such as time or frequency-domain response.

E. Desired filter specification

The desired FIR filter specifications will not be similar to all the Impulses waveforms defined in IEC-TDG (Test Data Generator) 61083-2, of which parameters to be evaluated. Since all the waveforms are of different category and of different characteristics. Hence, the table I & II give the values of prime specifications for Equi-ripple & Kaiser filter respectively with the various data for passband ripple ($r_p$) and stopband ripple ($r_s$).

<table>
<thead>
<tr>
<th>Data</th>
<th>CASE 03</th>
<th>CASE 04</th>
<th>CASE 08</th>
<th>CASE 09</th>
<th>CASE 13</th>
<th>CASE 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_p$</td>
<td>0.28</td>
<td>0.21</td>
<td>0.32</td>
<td>0.26</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>$r_s$</td>
<td>42.0</td>
<td>40.0</td>
<td>45.0</td>
<td>45.0</td>
<td>40.0</td>
<td>42.0</td>
</tr>
<tr>
<td>$f_p$</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
<td>3.50</td>
</tr>
<tr>
<td>$\Delta f$</td>
<td>0.28</td>
<td>0.21</td>
<td>0.32</td>
<td>0.26</td>
<td>0.19</td>
<td>0.28</td>
</tr>
<tr>
<td>$f$</td>
<td>3.78</td>
<td>3.71</td>
<td>3.82</td>
<td>3.76</td>
<td>3.69</td>
<td>3.78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data</th>
<th>CASE 03</th>
<th>CASEE 04</th>
<th>CASE 08</th>
<th>CASEE 09</th>
<th>CASE 13</th>
<th>CASE 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>413</td>
<td>413</td>
<td>413</td>
<td>413</td>
<td>413</td>
<td>413</td>
</tr>
<tr>
<td>$\beta$</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>$f_p$</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

IV. PERFORMANCE TEST USING IEC TEST DATA

Both the filters viz. Kaiser window and Equi-ripple filters were verified as accurate in determining impulse parameters by testing them against the IEC 61083-2 impulse test data.

There are 15 types of lightning impulse waveforms (CASE 01 to CASE 15) specified in IEC-TDG 61083-2 for testing software accuracy [4]. Noise levels in these test waveforms range from about 0.4% (digitizing noise only) to 10% (front oscillations) of the peak values. Tests results using these waveforms are listed in Tabular forms.

It was found that both filtering methods worked well on all cases and the frequency of oscillations and duration of overshoot are calculated [6], which are compiled with the standards. It can be noted that apart from a narrow dead frequency range from 0.5 MHz to about 3 MHz, which depends upon $T_f$ of the impulse, where allowable disturbances are still questionable, the digital filters can effectively eliminate noises of all other frequencies in the impulse waveforms.

Fig. 4 shows the waveforms of a Noisy Lightning Impulse with slow oscillations (LISL). When filters applied to the noisy measured data, it can be observed that the ripples has been reduced and nearly smooth curve has obtained as shown in Fig: 4. It can be noted from the graphs that measured wave form has not deformed much when filters are applied to it.

Fig. 5 Measured impulse CASE08 with its mean and residual curves

The prime parameters of the case 08 like $V_p$, $T_f$ and $T_2$ were calculated from the above graphs and are described in Table III.

From the Table III it is clear that prime parameters in this case were obtained with $<1\%$ and $<0.1\%$ for peak value $V_p$ and time parameters respectively.

In case of smooth waveform the measured parameters may be correct as per std. IEC 60-1.

But when these waveforms are superimposed back with oscillations it is necessary to draw a mean curve in order to determine the frequency of oscillation and/ or amplitude of oscillation, and obtain the residual curve by subtracting the same from the original measured curve [8]. These curves are shown in figure 5.
TABLE III. PRIME PARAMETERS OF IEC-TDG CASE 08

<table>
<thead>
<tr>
<th>CASE08</th>
<th>Peak voltage Vp in KV</th>
<th>Front time T1 in μs</th>
<th>Tail time T2 in μs</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-filter</td>
<td>1061.57</td>
<td>1.67000</td>
<td>48.1732</td>
</tr>
<tr>
<td>Equi-ripple filter</td>
<td>1061.44</td>
<td>1.69783</td>
<td>50.6950</td>
</tr>
<tr>
<td>Kaiser filter</td>
<td>1051.76</td>
<td>1.67000</td>
<td>49.6210</td>
</tr>
</tbody>
</table>

This residual curve is then filtered and again superimposed back to the fitted mean curve. By this method the frequency of oscillation and corresponding amplitude of oscillation were evaluated and are tabulated in Table IV.

TABLE IV. RESIDUAL PARAMETERS OF IEC-TDG CASE 08

<table>
<thead>
<tr>
<th>CASE08</th>
<th>f in KHz</th>
<th>A in KV</th>
<th>% Of Amp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-filter</td>
<td>467.46</td>
<td>52.00</td>
<td>4.90</td>
</tr>
<tr>
<td>Equi-ripple filter</td>
<td>416.72</td>
<td>33.08</td>
<td>3.09</td>
</tr>
<tr>
<td>Kaiser filter</td>
<td>420.5</td>
<td>50.58</td>
<td>4.81</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The accurate determination of Lightning Impulse parameters was obtained with the application of FIR digital filters. The accuracy limit for amplitude of oscillation / overshoot as per the standard IEC 60-1 is up to 5% of Vp and it was achieved with digital filter technique.

If we consider the uncertainty limits for the parameters Vp & T1 the measurement uncertainty can be reduced by using digital FIR filters. But, on the other hand digital filters will introduce their own uncertainty because of deformation of the desirable signal components. Thus, uncertainty considerations of the filtering process include two fold i.e. uncertainty caused by the noise residue and by signal deformation. But, with proper designing methods and effective mathematical procedures it is possible to obtain precision evaluation of Lightning impulse parameters. These FIR filters were shown to be particularly desirable and accurate for reference and approved measurement systems.

ACKNOWLEDGEMENT

Authors wish to thank the management of CPRI to publish this paper.

References