CHAPTER 5

FILTER BASED TECHNIQUES FOR FAILURE IDENTIFICATION

5.1 INTRODUCTION

One of the prime motivations for improved methods of failure identification was the need for eliminating subjectivity associated with visual comparison. While the transfer function has provided a better basis of comparison, especially with reference to chopped waves, the reliance on the human eye has not been eliminated. We hence propose four filter based methods, that can eliminate subjectivity. The preceding sections have provided a wealth of data on the likely changes occurring during faults. At the same time, certain precautions are to be observed. Specifically, a shift of poles and the addition of new poles serves as a criterion of failure. In practice, it is occasionally observed that certain deviations between transfer functions recorded at reduced voltage and those at full voltage exist. A prime reason is the poor signal to noise ratio at higher frequencies (Leibfried and Feser, 1992). An extensive set of simulations were hence performed to quantify those changes that do not stem from failure. Considerable assistance was also taken from records in the IEC 722. To give one example, Figure 14 of IEC 722, (reproduced here as Figure 5.1) was digitised with a high performance image processing system. This has proved a big boon as the entire records accumulated via analog oscilloscopes can also be interpreted. The changes in the transfer function as a result of a fault are shown in Figures 5.2a and 5.2b. In addition, a
Figure 5.1 LI-FW failure (Figure 14 of IEC 722)

Figure 5.2a Tf without fault of Figure 5.1
Figure 5.2b Tf with fault of Figure 5.1
detailed study was made of the failure cases recorded in the laboratory over the last ten years. Some of the critical cases are shown in Appendix A3.

5.2 FILTER BASED METHODS FOR FAULT IDENTIFICATION

IEC 722, provides a number of case-studies concerning failures during impulse testing. In the laboratory we have been able to make a study of over a thousand transformers of rating upto 10MVA, 550kV of which failures amount to about hundred. Many of these can be attributed to a similar cause. For example, a number of cases concern a failure of a bushing to the tank. While it recognised that appearances of failures are likely to vary from case to case, a perusal of these records enables an estimation of probable deviation in waveforms as a result of internal faults. As has been explained earlier, transfer function based comparisons should also elicit identical 'Pass/ Fail' type of responses. Of particular importance are those cases which show minor deviations in the temporal records but in actuality do not constitute failure. Minor variations in firing during the front of wave of the order of 1 us result in changes in the current oscillograms as is shown in Figure 21 of IEC 722. Any objective criterion for assessment must hence address itself to these issues. We begin with a fourier transform based method of comparison of transfer functions. Consider two transfer functions obtained during the reduced full wave and full wave test respectively. From IEC 1083 it is known that the maximum error in the measurement of voltage or current is 2%. As a result, for a worst case analysis, the two transfer functions can be vertically displaced by a maximum of 8%. Such cases have been practically demonstrated by Vaessen and Hanique (1992). For a reliable estimation of failure a mere displacement should not be construed as a fault. Similarly, at the higher
frequencies where results are vitiated by quantisation noise, meaningful comparison is difficult. Hence, as a first step, a band pass filter is used that cuts of the DC value and the values that are dictated by noise. A fourier transform of the resulting transfer function is then obtained. A comparison of the fourier transforms of the transfer functions taken at reduced and full voltage yields an objective criterion of failure identification. As a result of simulations and after a study of all the failures described earlier, we can state that a deviation of more than 1% of the two transforms is indicative of failure. Figure 5.3 shows a comparison of the transforms of Figures 5.2a and 5.2b from which an objective identification is readily possible. Figure 5.4 shows the percentage difference of the transfer functions.

5.2.1 Digital filtering of Transfer functions

A refinement of the above procedure involves digital filtering of the transfer functions. Two classes of digital filters, (FIR and IIR) are utilised for the purpose. The FIR filters comprise three moving average filters of 3, 9 and 21 points. The outputs of the filters for the case of the transfer function of Figure 5.2b is shown in Figure 5.5. Figures 5.6a - 5.6b show the percentage differences in the respective filter outputs between the unfaulted and faulted cases.

The IIR filter design follows the procedure adopted in designing 1/3 octave filters. Three band pass filters with Butterworth characteristics are designed. The outputs from each of the filters are used and the two transfer functions compared. One distinct advantage of this method in that it enables an identification of partial discharges which was not possible in the earlier
Figure 5.3  Percentage difference between Transforms of Tfs of Figures 5.2a, 5.2b

Figure 5.4  Percentage difference between Tfs of Figures 5.2a and 5.2b
Figure 5.5 Outputs of FIR filters for the case of figure 5.2b

Figure 5.6 Percentage difference between filter outputs of Figures 5.2a, 5.2b
The IIR filter characteristics are described either by difference equations or by Z transforms. (Both options have been described for the first filter alone.) They are as follows:

\[ y(n) = 5.1359y(n-1) - 11.4331y(n-2) + 14.0660y(n-3) - 10.0799y(n-4) + 3.9924y(n-5) - 0.68557y(n-6) + 0.0006991x(n) - 0.0020973x(n-2) + 0.0020973x(n-4) - 0.000699x(n-6) \]  
\[ (5.1) \]

\[ \frac{0.0006991 - 0.0020973z^{-2} + 0.0020973z^{-4} - 0.000699z^{-6}}{1-51359z^{-1} + 114331z^{-2} - 14.0660z^{-3} + 10.0799z^{-4} - 3.9924z^{-5} + 0.68557z^{-6}} \]  
\[ (5.2) \]

**Filter II**

\[ TF = \frac{3.1696 \times 10^{-3} - 9.5088 \times 10^{-3} (z^{-2} - z^{-4}) - 3.169 \times 10^{-3} z^{-6}}{1 - 3.5661z^{-1} + 6.6160z^{-2} - 7.3728z^{-3} + 5.3232z^{-4} - 2.3064z^{-5} + 0.5209z^{-6}} \]  
\[ (5.3) \]

**Filter III**

\[ TF = \frac{0.019z - 0.5902z^{-2} + 0.05902z^{-4} - 0.0197z^{-6}}{1 + 0.164z^{-1} + 1.8750z^{-2} + 0.8319z^{-3} + 1.4007z^{-4} + 0.2778z^{-5} + 0.2659z^{-6}} \]  
\[ (5.4) \]

The procedure for designing these filters has been described in a number of works (Taylor, 1988, Proakis and Manolakis, 1989). As a case study the results of using this method indicate a partial discharge in the modal analysis transfer functions. Similarly a clear failure is indicated for a 10% fault of the Abetti coil. The unfaulted transfer function and the filter outputs for this coil are shown in Figure 5.7.
Figure 5.7  IIR filter outputs of $T_f$ of Abetti coil
5.2.2 The spectral moment method

Exploring the notion further we arrive at a final method for comparison using the method of spectral moments. The first spectral moment can be defined as

\[ X(f) = \int_{-\infty}^{\infty} \text{Fodo} \]

In lieu of the complete moment, partial movements at locations corresponding to the poles alone can be evaluated. Using the principal moments, an objective assessment is again possible. It must be mentioned that this method has the further advantage of eliminating noise to a great extent. Figure 5.8 shows the percentage difference in the spectral moments for the case of data from IEC 722.

5.3 FILTERING IN THE TIME DOMAIN

In the previous section, three objective criteria for failure identification were developed that stemmed from filtering concepts in the frequency domain. The first technique involved a fourier transform method that essentially gave a 'Yes' or 'No' type of answer. A Digital approach with three band pass filters permitted a better categorisation of responses, while the spectral moment method featured a good immunity to noise. All these techniques necessarily involve a digital data acquisition system with fast A-D converters, fourier analysis and a lot of computation. It would be worthwhile exploring the feasibility of invoking the essential features of filtering in the time domain itself. Such a method would have the advantage of being low cost and reliable. The impetus for this method arose partly from the efficacy of the method using spectral moments delineated earlier.
Figure 5.8 Comparison of spectral moments of Figures 5.2a, 5.2b
The arrangement for the time domain method uses analog filters. Three low pass filters each are connected to the low voltage arm of the divider and the output of the current shunt. The cut off frequencies of the filters are designed to have a geometric progression such that:

\[ f_2 = \sqrt{f_1 f_3} \quad (5.6) \]

\( f_3 \) has been decided on the basis of a 95% cross-spectral energy density criterion. The output of each filter is given to an active op-amp based peak detector whose circuit is shown in Figure 5.9. The utility of this method can best be appreciated by a reference to the accompanying figures. Figure 5.10 shows a standard lightning impulse voltage at reduced voltage impressed across the Abetti coil along with the filter outputs. Similarly the current waveform and the corresponding filter outputs are depicted in Figure 5.11. The test is repeated at full voltage and the filter outputs again obtained. Table 5.1 shows that with no fault, the ratio of current to voltage for each filter is identical.

**Table 5.1: Filter outputs for a 1.2 / 50 μs impulse test on the Abetti coil**

<table>
<thead>
<tr>
<th>Filter No</th>
<th>Peak Output at Reduced Voltage</th>
<th>Peak Output at Full Voltage</th>
<th>Current at reduced voltage</th>
<th>Current at full voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.82</td>
<td>5.64</td>
<td>1.325</td>
<td>2.65</td>
</tr>
<tr>
<td>2</td>
<td>2.57</td>
<td>5.14</td>
<td>1.325</td>
<td>2.65</td>
</tr>
<tr>
<td>3</td>
<td>1.98</td>
<td>3.96</td>
<td>1.325</td>
<td>2.65</td>
</tr>
</tbody>
</table>

For the case of an impulse wave chopped at 2 μs, the voltage and current are shown in Figure 5.12a and 5.12b respectively. The current filter
Figure 5.9  Schematic of a peak detector circuit

Figure 5.10  Voltage and filter outputs for the Abetti coil energised by a LI

Figure 5.11  Current and filter outputs for the Abetti coil energised by a LI
outputs under no fault and with a 10% fault are shown in Figures 5.12c and 5.12d respectively. Table 5.2 shows the various relevant output values from which failure identification is immediate.

Table 5.2 Filter outputs for an impulse test chopped at 2μs on the Abetti coil

<table>
<thead>
<tr>
<th>Filter No</th>
<th>Peak Value (v) of filters in current circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without fault</td>
</tr>
<tr>
<td>1</td>
<td>2.68</td>
</tr>
<tr>
<td>2</td>
<td>2.07</td>
</tr>
<tr>
<td>3</td>
<td>0.76</td>
</tr>
</tbody>
</table>

For the case of an impulse wave chopped at 6 μs, the voltage and current are shown in Figure 5.13a and 5.13b respectively. The voltage filter outputs under no fault and with a 10% fault are shown in Figures 5.13c and 5.13d respectively. Table 5.3 shows the various relevant output values from which failure identification is immediate. The method is thus fully validated.

Table 5.3 Filter outputs for an impulse test chopped at 6μs on the Abetti coil

<table>
<thead>
<tr>
<th>Filter No</th>
<th>Peak Value (v) of filters in the current circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without Fault</td>
</tr>
<tr>
<td>1</td>
<td>6.87</td>
</tr>
<tr>
<td>2</td>
<td>5.43</td>
</tr>
<tr>
<td>3</td>
<td>2.19</td>
</tr>
</tbody>
</table>
Figure 5.12a: Voltage / current for the Abetti coil energised by CLI (time to chop 2 µs)

Figure 5.12c: Voltage filter outputs with and without a 10% fault on the Abetti coil
Figure 5.13a Voltage / current for the Abetti coil & b energised by CLI (time to chop 6 µs)

Figure 5.13c Current filter outputs with and & d without a 10% fault on the Abetti coil
5.3.1 Design of lowpass filters

For the application under consideration it is quite obvious that the attenuation characteristic needs be monotonic. Amongst the class of low pass filters that exhibit such a feature the following are the principal ones:

- Butterworth
- Bessel
- Papoulis
- Synchronously tuned

The choice among these is governed by the following criteria:

- Attenuation steepness
- Transient characteristic
- Order Number

It has already been shown that the Papoulis filter (based on Legendre's polynomials) exhibits the highest attenuation in the stop band. In view of its oscillatory step response, such a filter was not considered. The synchronous filter exhibits ideal step response, with very poor attenuation. As a compromise, Butterworth filters of order 3 have been used in this application. The characteristics of 3rd order filters have been compared in Figure 5.14.

In this chapter a number of signal processing methods have been developed permitting an objective evaluation of the impulse test. It remains to fortify these methods by a consideration of insulation behaviour. This task is taken up in the ensuing chapter.
Figure 5.14 Characteristics of low pass filters of order 3

1. Legendre
2. Butterworth
3. Bessel
4. Synchronously tuned
CHAPTER 6

FAILURE ANALYSIS USING ADDITIONAL SUPERIMPOSED VOLTAGES

6.1 INTRODUCTION

The previous chapter highlighted the role of signal processing methods in ensuring an objective evaluation of impulse testing. Any success of these methods should however be underpinned from a study of insulation behaviour. We now undertake this task of unravelling some of the pertinent features concerning breakdown so as to develop alternative methods of failure identification. Each of these are to be construed as a progression of techniques rather than entirely new ones.

6.2 BREAKDOWN IN SOLID INSULATING MATERIALS

Breakdown in organic insulators is always 'catastrophic' in the sense that it is irreversible and destructive resulting in a narrow breakdown channel between the electrodes (Dissado and Fothergill, 1992). In addition, all catastrophic breakdown in solids is electrically power driven and ultimately thermal. It is meant that the discharge track involves at least the melting and probably the carbonisation or vaporisation of the dielectric. It is only in the above sense that we have used the term breakdown and subsequent methods developed are for recognition of such activity in a small region in an otherwise intact transformer.
An explicit recognition of this statement is necessary as the term 'breakdown' has also been used to describe processes in which a considerable increase in current stems from a small voltage charge. Such processes may or may not be catastrophic being governed by the nature of the power sources. A familiar example of such an event occurs in a reverse biased semiconductor junction. In polymers such situations are possible but shall not be deemed as breakdown unless it leads to destruction of at least a local area. In terms of fundamental mechanisms, the duration of the lightning impulse test dictates that either electric or thermal mechanism operate. Dissado & Fothergill treat these mechanisms in detail. To reiterate our stand, we understand a breakdown as follows:

Most good insulating material conduct to some extent. At working stresses the leakage current is negligible and is expected to remain stable as voltage is raised. At some high value of the field however an unstable situation will develop and the current will increase by many orders of magnitude without any increase of the field. During this process the power dissipated in the insulator will melt and probably vapourise it forming a narrow conducting channel between the electrodes. Under such circumstances the insulator will have been irreversibly converted to a conducting state. This definition provides a simple method for detecting failure other than a full wave test. It has been shown that failure in a transformer is associated with a shift of poles. If the pole shift were to be caused by an irreversible conducting path it stands to reason that even a low voltage swept frequency unit would be capable of detecting shifts. A low cost variable frequency oscillation is designed for this purpose. A gradient method for locating poles is utilised in order to reduce the time for detecting
the poles. The scheme which is based on the Fibonacci sequence is as follows:

The Fibonacci sequence, \( F_n = \{1, 1, 2, 3, 5, 8, 13, 21, 34, 55, \ldots \} \) forms the basis of the most efficient sequential-search technique. Each number in the sequence is obtained by adding together the two preceding numbers; exceptions are the first two numbers, \( F_0 \) and \( F_1 \), which are both 1.

The Fibonacci search is initialised by determining the smallest Fibonacci numbers that satisfy \( F_N \geq b-a \), where \( \varepsilon \) is a prescribed tolerance and \([a, b]\) is the original interval of interest. Set \( \varepsilon' = (b-a)/F_N \). The first two points in the search are located \( F_{N-1}\varepsilon' \) units in from the end points of \([a, b]\), where \( F_{N-1} \) is the Fibonacci number preceding \( F_N \). Successive points in the search are considered one at a time and are positioned \( F_{j}\varepsilon' \) (\( j = N - 2, N - 3, \ldots, 2 \)) units from the newest endpoint of the current interval. In this procedure we can state in advance the number of functional evaluations that will be required to achieve a certain accuracy; moreover, that number is independent of the particular unimodal function. In practice, the poles are initially determined with the help of the transfer function computed at reduced voltage. After the impulse test, the search is confined to these peaks and the changes are obtained using the Fibonacci sequence.

Figure 6.1 shows the voltage and current through a 6.6kV control transformer that failed during an impulse test. The non-sinusoidal current clearly indicates the creation of a new pole in this case.
Figure 6.1 Failure detection using a low voltage variable frequency source.

(current shows non-linearity when energised by a voltage whose frequency is equal to that of a pole)
6.3 LOW VOLTAGE UNIT SUPERIMPOSED ON THE 50Hz VOLTAGE

Permanent conducting channels stemming from failure during impulse tests are fairly easy to detect. It is possible that during a sequence of impulse tests a tree like discharge occurs within the bulk material but is unable to form a complete conducting path. Evidence for such occurrences is readily available as described by Sillars (1973). It was shown that the growth of one or more tubular fissures (that cumulatively result in breakdown) during the application of successive impulses was largely random. Today we would describe the process as having a fractal nature. Figure 6.2 shows this feature of a cellulosic paper based board subjected to an AC voltage under moist conditions. On subsequently energising the sample with an impulse voltage it is clearly observed that the growth of the discharge still retains its fractal nature and although the current traces change during the impulse voltage application, it essentially, retains an insulating nature between electrodes. As such, a low voltage unit might be insufficient for identifying the failure.

Equipment that have served in site for a few years sometimes show similar degradation patterns as has been reported by Udayakumar (1988). If the transfer function method is to serve as an improved technique, it must also cater to such contingencies. It is hence proposed to perform a frequency sweep at low voltage that is superimposed on the power frequency voltage. Pole locations can again be determined and a shift would again be indicative of failure. One example of the voltage applied is shown in Figure 6.3.
Figure 6.2 Fractal breakdown associated with surface discharge in moist Hylam boards

(Electrode: circular, quasi 3D)
current response shows a change in the
harmonic content before and after fault.

Figure 6.3a Failure detection using a low voltage
variable frequency source superimposed
on a 50 Hz wave

6.3b Expanded view of 6.3a
6.4 SUPERIMPOSITION OF A LIGHTNING IMPULSE DURING POWER FREQUENCY

During the testing of indoor cast resin voltage transformer it is often observed that changes in the current shape in the form of a single spike occurs as compared with the reduced full wave value. The location of the spike is found to vary at random during successive impulse applications. It would be tempting to categorise it as a partial discharge process. However, we are concerned with the potential impact of such occurrences on the normal power frequency behaviour too. The crucial decision is whether such deviations can be allowable. Hence we propose that for such situations the standard lightning impulse test be applied at the crest of a normal power frequency voltage itself. Figure 6.4 shows the proposed arrangement. Of course, such an arrangement by itself is not new as some older standards initially employed such a scheme. There is also recent interest in the so-called reverse polarity impulse test as a requirement for the EHV range of transformers. (Wagenaar, Schneider and Fleeman, 1994). The accent here is on identifying irreversible changes in the current shape as the result of the application of the impulse voltage. Figure 6.5a and 6.5b show one example of the results using the proposed technique.

6.5 THE OSCILLATING IMPULSE VOLTAGE

While the above method is completely feasible, it would be convenient if a scheme could be thought of that combines the features of an alternating voltage and at the same time attains high values associated with the lightning impulse. The oscillating impulse generator is one such apparatus. It has found applications in the on-site testing of GIS equipment.
A Impulse circuit
B Normal frequency circuit

C\textsubscript{g} = capacitors of impulse generator
R\textsubscript{g} = main shunt resistor
R\textsubscript{bo} = series resistor, external to generator
R\textsubscript{bi} = series resistor, internal to generator
C\textsubscript{j} = auxiliary capacitor to control waveshape
G = protecting gaps (high-vacuum)
RG = test gap (rod gap)
R\textsubscript{d} = main resistor of voltage divider
R\textsubscript{i}, R\textsubscript{o}, R\textsubscript{t} = auxiliary resistors of voltage dividers

Figure 6.4 Schematic of a method for energising a transformer with LI superimposed on a 50 Hz wave (Hagenguth, 1944)
Figure 6.5a Failure detection using a LI superimposed on a 50 Hz wave

6.5b Expanded view of 6.5a showing superimposed LI waveforms and response
Here we utilise the equipment for identifying irreversible changes in the current shape.

The behaviour of a winding subjected to different excitations from the generator are shown in Figures 6.6a - 6.6b. It can be seen that a considerable improvement in certain high frequency components of the current is feasible. Such a feature improves the signal to noise ratio that is so crucial to the transfer function method. The utility of the method can be best appreciated by considering Figure 6.7 where no failure is observed at low voltage but is evident at a slightly higher voltage. Figure 6.8a corresponds to a standard lightning impulse at reduced value. The oscillating impulse generator is charged such that it achieves a peak value corresponding to a higher BIL level (Figure 6.8b). Finally, the current shape at full BIL is shown in Figure 6.8c. The improved identification with the oscillating impulse voltage is clear.

6.6 ENDURANCE TESTING AND ITS RELEVANCE TO FAILURE IDENTIFICATION

The number of voltage applications that can be applied during an impulse test is limited. In case of ambiguity one can at the most repeat the test. Would it be possible to devise a test that can provide greater confidence with regard to the insulation integrity of a transformer? Such a question was posed by a CIGRE group with regard to voltage transformers and the answer is the endurance test. This essentially applies to oil immersed voltage transformers where 600 impulses (chopped on the tail) having a value of 75% BIL of the equipment is utilised. We have done one such test for the case of a voltage transformer and found that it withstood
Figure 6.6  Response of a 11 kV transformer to oscillating impulse voltages
Figure 6.7 Failure detection in a VT using an oscillating impulse generator
Figure 6.8  Failure detection in a Control Transformer using an oscillating impulse generator
Figure 6.9 FW-LI on a 11 kV cast resin VT
the test although minute spikes did occur at the full BIL level. Figure 6.9 shows the time domain records during the first impulse and also at the 100th impulse.

We have also conducted a number of tests on polyester insulated copper wire on which we checked the utility of the endurance tests. Failures occur in a number of cases as shown in Figure 6.10. Figure 6.11 shows a voltage transformer that failed during an impulse test. All the methods suggested in this chapter proved to be successful in identifying the failure prior to the transformer being broken. With such a clear appearance of the catastrophic event, we close the issue of impulse testing of transformers. It would be worthwhile to study the utility of frequency domain methods for checking coil deformations.
Figure 6.10: SEM photograph of puncture of enamelled wire

Figure 6.11: Appearance of a 11 kV VT that failed to withstand the FW-LI