New Methods for Improving the Reliability of Non-Destructive High Voltage Impulse Testing

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Abstract

Non-destructive hv impulse tests are normally performed by the comparison method. Two or more impulse voltage and current records are compared with each other at different voltages. If they show no differences in the wave-shape then the insulation has passed the test. For such measurements, a highly accurate and disturbance-free measuring system is necessary. With digital signal processing the accuracy and reliability of the measurements can be improved. Two methods are introduced in this paper. The influence of and limitations imposed by the performance of the digitiser are discussed as a third point.

1. The transfer function method transforms the time signals of the impulse current and voltage in the frequency domain. By dividing the two spectra, the resulting admittance over frequency is calculated. Differences in the admittance spectrum of consecutive impulses can be an indication of an insulation failure.

2. The coherence function is used to check an impulse measuring circuit under high voltage conditions. The coherence check can detect bandwidth limitations caused by inadequate impulse dividers, for example, and noise penetration by electromagnetic interferences.

3. Digital recorders have become an established tool for performing transfer and coherence function analysis. The limits caused by the recording process, predominantly the digitising error, are discussed with respect to characteristic quantities of digital recorders.

Introduction

To perform non-destructive impulse tests on high voltage insulation the international standards prescribe comparison tests. For power transformer testing, IEC 76-3, for example, demands for a sequence of one lightning impulse between 50% and 75% of the full test voltage, and three subsequent impulses at full voltage. The criteria for passing the test is:“ The absence of significant differences between voltage and current transients recorded at reduced voltage and those recorded at full test voltage constitutes evidence that the insulation has withstood the test.“ It further states: “The detailed interpretation of the oscillographic records and discrimination of marginal disturbances from true records of failure require a great deal of skill and experience“/1/.

The conventional method was to compare the voltage on Polaroids taken by an analogue impulse oscilloscope. With a digital impulse analysing system the recorded and digitised wave forms can be scaled to the same magnitude and the time origin can be shifted in a way to minimise the difference between the superimposed records. The subtraction of the two records is performed mathematically by the computer and is displayed to the user showing up only the differences of the two graphs (Figure 1).

However with non high quality impulse generators some differences between the two generated test impulses will also show up in the difference record. This happens e.g. with different trigger mechanisms between reduced and full impulse voltages, resulting in non linear voltage shapes. Another reason for deviations is the noise imposed on the measured quantities due to electromagnetic interference. Then the interpretation of the records becomes a difficult task and disagreements between the test engineer and the inspector may follow.

With enhanced analysis of the recorded waveforms however, some support and help can be provided to clarify and improve the quality of the measurements.

The Transfer Function Analysis

To receive the transfer function the frequency spectras of the recorded voltage u(t) and current i(t) signals are calculated by FFT resulting in u(f) and i(f). The quotient of i(f) and u(f) is called transfer function TF

$$TF(f) = |i(f) / u(f)| = 1/ |Z(f)|$$

where Z(f) reflects the impedance spectrum of the transformer under test.

Thus neither the amplitude nor the shape of the generated wave form affects the shape of the transfer function. Deviations which show up in the time signal are eliminated in the transfer function. In other words the transfer function shows a fingerprint of the test object which is independent of the excitation.

Physically TF reflects the electrical characteristics of the winding and reveals its natural oscillations. Each resonant pole on the transfer function plotted against frequency corresponds to a natural resonance of a winding section /2/.

In practise the two obtained transfer functions of the full and reduced voltage levels are superimposed (Figure 1). For an undamaged winding the frequency behaviour should be constant and no deviations will show up. A breakdown over a small portion of the winding will change the inductance and/or capacitance distribution of the winding and hence will change the frequency of a given resonance pole.

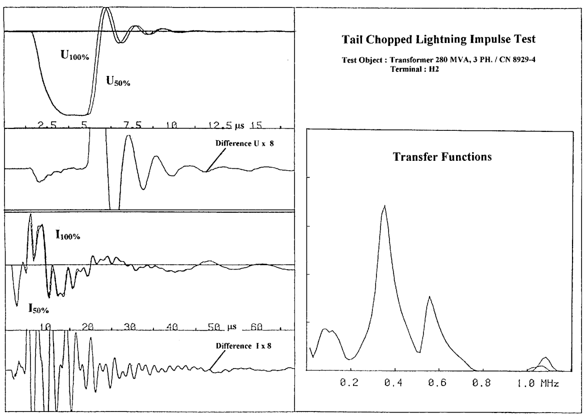


Fig. 1. Transfer function obtained from two impulses chopped at a slightly different time. Although, the test impulse and the neutral terminal current show a marked difference, but the transfer function remains practically unchanged, and this confirms the winding integrity.

It is usually easier to detect the minute difference signal by an observed pole shift on the transfer function, rather than by comparison of the impulse records, where the small glitch may be dwarfed by the impulse.

In practise some effects influence the performance of this method.

The voltage dividers, current shunts and at least the digital recorders have limited bandwidths. Normally the voltage divider is the critical element in the measurement chain with a bandwidth of some MHz, decreasing with the increasing nominal voltage value. Also the frequency content of the exciting waveforms like full or chopped impulses have smaller amplitudes in the upper frequency range. The quantization errors of the digital converter and its limited dynamic resolution limit the upper frequency of the transfer function.

The transformer itself can change the transfer function without having any defects. At first, saturation of the core may be reached if several impulses of the same polarity are applied, since they add to the magnetic core remanence. A second source of non-linear behaviour of transformers are built in semiconductor (ZnO) lightning arresters, which may operate within the test voltage range, and effectively do change the transfer function.

However, changes of the transfer function due to core saturation occur usually at the impulse tail, and the clipping of voltage across a winding section protected by the arrester has a distinct pattern. These effects can be easily recognised by experienced inspectors and there is little chance to take such symptoms for an internal breakdown or partial discharge.

The electromagnetic noise is the main factor which imposes limits on the high voltage measurement and on the practical use of the transfer function. In following the principal mechanism of interference will be discussed.

Electromagnetic Interference in HV Test Laboratories

There are two mechanisms of interference coupling to the impulse measuring circuit. The interference can be conducted to and/or induced in the digital recorder, its input attenuator, coaxial cables, the divider low voltage arm and current measuring shunt.

Transformer testing requires simultaneous measurement of the voltage and current records, and these two signals are brought to the recorder from the divider and shunt by coaxial cables. The grounding points of divider and shunt are connected to the laboratory grounding mesh at different locations separated by a distance of several meters.

A considerable potential difference can develop between these locations under transient conditions. The transient voltage drop on the grounding mesh impedance is caused by the current flowing in this mesh. The capacitive current is injected to the ground mesh by a rapid rise of potential U of the impulse generator HV electrode, at the time of generator firing, and also at the instant of impulse chopping. The mechanism of current injection into the grounding mesh is presented schematically in figure 2.

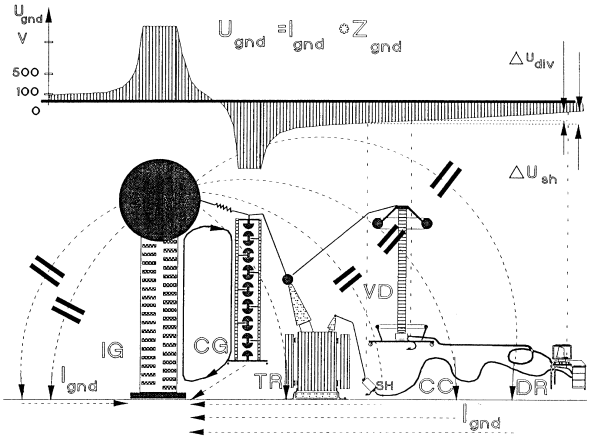


Fig. 2. HV impulse test set up. IG impulse generator, CG chopping gap, TR transformer under test, VD voltage divider, SH current measuring shunt, DR digital recorder, CC coaxial cable, Ugnd voltage drop on the ground mesh impedance, Ignd capacitive current collected by the ground mesh, DUdiv and DUsh potential difference between an input end of the voltage divider and shunt cable.

An order of magnitude of the total capacitive current I_C can be estimated for a typical impulse test set up as follows:

$$I_C = C_g \bullet \Delta U/\Delta t \approx 40 \text{ kA}$$

with:

Cg ~ 2 nF - ground capacitance of the impulse generator top electrode,
U ~ 2 MV - impulse peak voltage,
Dt ~ 0.1 µs - rise time of the top electrode potential

Considering the magnitude of current flowing in the laboratory grounding system, a low impedance grounding mesh covering the impulse test area is essential to reduce the transient voltage difference between the input end of the voltage divider and shunt coaxial cable.

Conducted Interference

This voltage difference can be perceived as a source of transient interference voltage connected between the divider and shunt cable ends, and also between the grounding point of the digital recorder. The ground current flows then in the grounding mesh and in the coaxial cable shield, which forms a parallel path. A ratio of the cable shield current Ic to the grounding mesh current Imesh depends on the respective inductive impedance of these two paths, and is sometimes referred to as the grounding efficiency (GE). Although a high GE = Ic/Imesh≈-60 dB (1:1000) is desirable, many practical grounding systems are characterised by the modest grounding efficiency GE ≈ -40 dB.

A voltage drop Uc developed by the cable shield current Ic across the cable shield resistance represents the conducted interference, which is superimposed on the recorded signal. This interference shows up in form of a high frequency oscillation which often masks pertinent details of the recorded voltage and current wave forms.

There are two ways to reduce the conducted interference voltage: the first calls for selection of a high quality coaxial cable, which is characterised by a low resistance of the cable shield. The second method consists in a reduction of the cable current Ic, which results in an increase of the grounding efficiency. This can be achieved by installation of magnetic (preferably ferrite) cores around the coaxial cable, or installation of the cable in a steel pipe.

Although magnetic permeability of an ordinary steel pipe decreases at a few hundred kilohertz, this solution is often used since the steel pipe is inexpensive and provides also a mechanical protection of the coaxial cable. It has been shown that the steel pipe can reduce the cable current Ic up to four times, with respect to a non-magnetic, e.g. copper pipe.

Induced Interference

Firing of an impulse generator induces an electric and magnetic field component, which attains 50 to 100 kV/m and 500 to 1000 A/m, respectively, at the test laboratory floor level. These values have been measured at several HV laboratories stations, and are specified by the IEC as well as IEEE standards for testing of the shielding efficiency of electronic recording instruments.

In general, an unprotected, commercial digital recorder, computer or oscilloscope can not operate in the electromagnetic environment of a HV impulse test bay. To ensure a reliable operation of such instrument, it has to be installed in a Faraday cage type of shielding structure, and supplied from a properly conditioned power source.

The design of the electromagnetic shielding structure for a computer controlled signal acquisition system for use in HV impulse test area calls a serious research effort, and the cost of such work represents a significant part of the impulse recorder price.

The Coherence Check

The coherence function provides an indication of the areas where the ingress of noise made the signal processing not reliable. The coherence function is derived from all the time domain records used in the transfer function calculation. Assuming a linear behaviour of the examined winding, and an ideal, noise-free measuring system, the coherence shall be equal to unity over all the analysed frequency band.

A coherence function value lower than one indicates noise from interference or quantization or a winding fault.

The coherence function γ(f) is calculated as follows:

$$g\,(f) = \frac{\left|\underline{G}_{xy}(f)\right|}{\sqrt{G_{xx}(f)*G_{yy}(f)}} \quad , \quad G_{xx}(f) = \sum_{i=1}^{n} \frac{\left|\underline{U}_i(f)\right|^2}{n}$$

$$G_{yy}(f) = \sum_{i=1}^{n} \frac{\left|\underline{I}_i(f)\right|^2}{n} \quad , \quad \underline{G}_{xy}(f) = \sum_{i=1}^{n} \frac{\underline{U}_i^*(f)*\underline{I}_i(f)}{n}$$

Gxx(f), Gyy(f): *auto power spectrum (auto spectral density function)*
Gxy(f): *cross power spectrum (cross spectral density function)*
n: *number of sets*
U (f): *frequency spectrum (complex value) of the recorded voltage waveform*
I (f): *frequency spectrum (complex value) of the recorded current waveform*
U:* *complex conjugate value*

Gxx(f), Gyy(f), Gxy(f) are approximated that means averaged functions.

The resulting figure γ is reel and has a value between 0 and 1. A zero means that there is no correlation between the recorded signal, e.g. when there is only noise. On the contrary a value of one indicates that the signals are correlated, e.g. for ideal non distorted and noise free measurements.

The number of records taken for the evaluation influence the uncertainty of the coherence value. For practical purposes a number of records greater or equal three should be taken for reliable analysis results.

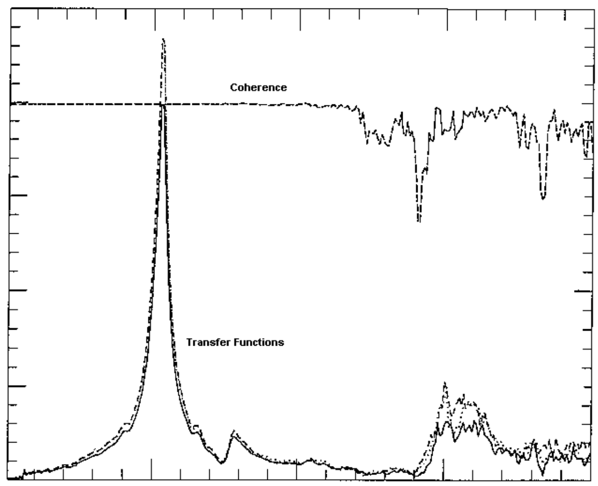
One important requirement for the use of the coherence analysis is that all the records which are used for the Coherence Function shall be taken on the same test object and with an identical test circuit configuration. No modifications in the test arrangement (e.g. moving of dividers, changing of cables and connections) shall be performed during the tests.

Checking the measuring circuit with the coherence function

With this test, the impulse measuring circuit can be qualified regarding the frequency range and the dynamic performance of the impulse measuring system. The advantage of this method against others is that the whole measuring circuit is qualified during a „life test“. This means that all components contributing to the measurement performance are taken into account, e.g. test object, high voltage connections, divider, low voltage connections, earthing and the digitizer. On the other hand the electromagnetic interference is in the same magnitude as in the real test. So, interference penetrating the measuring circuit will show up in the coherence analysis leading to lower coherence values /3/.

To perform this test, three (or more) voltage and current curve sets should be recorded at a reduced test voltage level including the test object. The voltage level should be adjusted in a way that it is high enough to produce electromagnetic fields in the same magnitude as in the real test, on the other hand the voltage should be so low, that an insulation failure or overstressing of the insulation can be excluded. Practical values are in the range between 40% to 70% of the test voltage. The standard lightning impulse is normally chosen for this test.

The coherence function derived from the records obtained with the standard lightning impulse is expected to decrease below unity in the frequency range above approximately 1 MHz. This is caused by the quantization error of a 10 bit digital recorder.



0 Figure 3 shows an example obtained from three records.

2 [MHz]

Fig. 3. Transfer Functions and Coherence of three records.

1

A low coherence at lower frequencies (some tens to hundred kilohertz) indicates a corruption of the recorded voltage and current curves by external noise. Most likely, an electromagnetic noise has penetrated the shielding system and got coupled into the measuring circuit. In such a situation, a revision of the shielding and grounding system of the impulse measuring circuit is recommended.

Conversely, a coherence function, that is equal (or near) to unity in the frequency range up to 1 MHz is an indicative of a sufficiently shielded measuring circuit.

Use of the coherence function during the impulse test

In the insulation test a different number of impulses of reduced and full voltages are normally applied to the test object. For the calculation of the coherence function the same number of sets as in the check described above should be taken at full (100%) and reduced test levels (e.g. 50%). Then the transfer functions and the coherence from these records are evaluated (see figure 3).

Interpretation of coherence functions

An internal insulation fault which has occurred at the full test voltage level will show up as a difference between the compared transfer functions. The coherence function helps to distinguish the difference between the compared transfer functions caused by the insulation fault, from a difference due to influences external to the transformer (noise, discharges, interference).

In the case of a fault in the winding, the coherence derived from the records taken at the full test voltage level, will show a low value in the frequency range where the difference between transfer functions shows up. Whereas, the coherence function calculated from the records taken at the reduced test level shall be close to unity in the same frequency range.

On the other hand, a low coherence value observed in the same frequency range in the coherence function derived from the full and from the reduced test level records is an indicative of an interference, rather than an internal fault.

It has to be remarked, that this interpretation is simplified for the sake of a clear understanding of the basic procedures. The most useful application of the coherence function is the check at reduced voltage levels. There an inadequate shielding and grounding can be identified and corrected.

Especially the interpretation and comparison of transfer and coherence function in the insulation test requires skill and experience from the user. Also this new method needs to be developed in the practical insulation testing before the analysis leads to reliable results.

Limits caused by the recording process:

Performing transfer and coherence function analysis requires exact time and, particularly, amplitude information regarding the initial signal. As both analysis tools perform a transformation of the original signal from the time domain to the frequency domain we can trust these transformations only to a certain upper limit. On one hand, the bandwidth or sampling rate of digital recorder determines

the highest frequency which can be recorded. On the other hand the amplitude resolution determines the smallest signal which can be recorded.

The frequency spectra of a smooth standard IEC impulse strongly drops when we look at higher frequencies. Even the steepest impulse, the front chopped lightning impulse, has very small components above 1 MHz.

Most commonly used digital recorders do have a bandwidth of ≥ 10 MHz and a sampling rate of ≥ 60 MHz. The bandwidth or sampling rate of the digital recorder is therefore not the main limiting factor and will be neglected in further discussions.

The excitation of a test sample - e.g. a transformer tested with a lightning impulse - is very low in amplitude for higher frequencies. The measured signal in the frequency domain [M(f)] is the result of the original impulse [E(f)] combined with the response function of the test sample [R(f)].

$$M(f) = E(f) * R(f)$$

According to this formula there are two solutions to extend the measuring range to higher frequencies:

1.) By means of impulses [E(f)] which contain larger high frequency harmonics.

2.) By an improved amplitude resolution.

The first solution has two main disadvantages:

Firstly, an impulse with shorter rise or chopping time would stress the transformer more. Secondly a modified impulse generator is required.

The second solution an improved amplitude resolution can be achieved with a higher number of bits and a improved noise suppression.

As an example transformer tests performed with digital recorders of different amplitude resolution were compared. The capacitive transferred current of the secondary winding and the impulse voltage were measured simultaneously.

To show the effect of the resolution clearly only switching impulses with low high frequency harmonics were used.

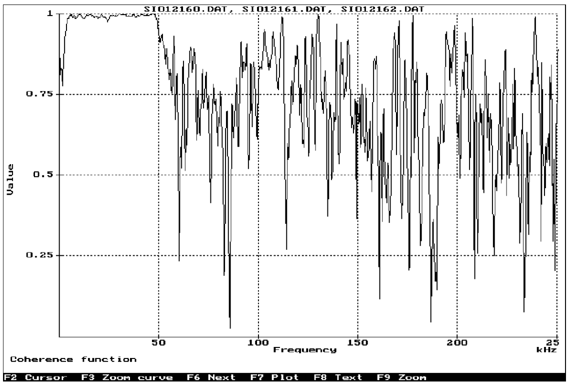


Fig. 4. Coherence of 3 switching impulses measured with 7 bits amplitude resolution. The coherence function shows a reliable measurement up to 50 kHz.

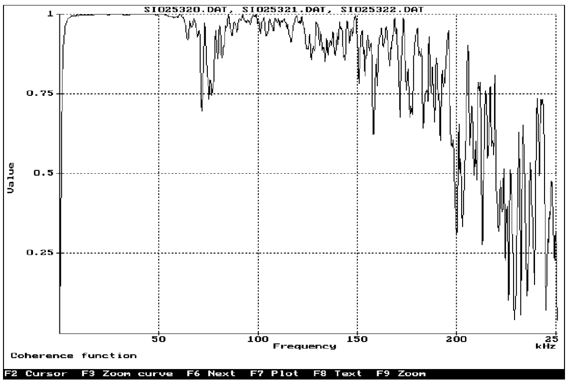


Fig. 5. Coherence of 3 switching impulses measured with 8 bits amplitude resolution. The coherence function shows a reliable measurement up to 70 kHz.

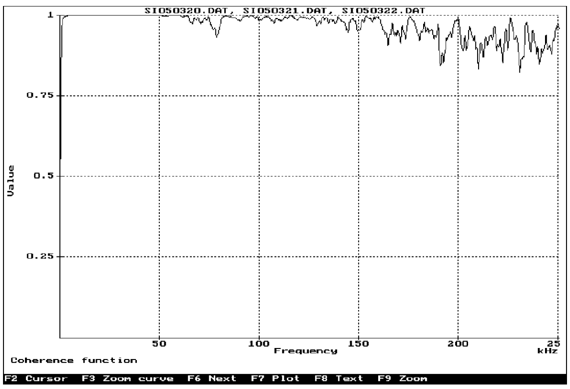


Fig. 6. Coherence of 3 switching impulses measured with 9 bits amplitude resolution. Another strong improvement has occurred.

Conclusions

Analogue oscilloscopes have more and more been replaced by hv-digital impulse analysing systems. Beside the recording, storing and documentation of tests they offer extended features which help the operator in evaluation and analysing of the test records. One of them, the transfer function, can be used to detect differences in the comparison test which are hardly to be seen in the time record.

However, the performance of the whole measuring system including HV dividers and shunts is strongly dependent on the electromagnetic shielding structure. The quality of the cables, the earthing and the shielding of the transient recorders influence the quality of the results.

The method of calculating the coherence of several impulse records provides an excellent indication of the dynamic behaviour and the immunity to interferences of a measuring circuit. From the practical point of view, a low coherence shall be considered as a warning. This warning tells the user that he has to improve his grounding and shielding system above that frequency that the spectrum of the HV-impulse is covering.

An improvement in the amplitude resolution of digital recorders will dramatically extend the frequency range of the transfer function and coherence function which are the best performing analysis tools. In the near future we will see if this improvement is of assistance with locating errors and extending quality control.

References

/1/ **IEC Publication 76-3**, Power Transformers, Part 3 : Insulation levels and dielectric tests, 1988.

/2/ **R. Malewski, E. Gockenbach , R. Maier, K.H. Fellmann, A. Claudi,** 'Five Years of Monitoring of Impulse Test of Power Transformers with Digital Recorders and the Transfer Function Method', Cigré 1992 Session, paper 12-201, Paris 1992.

/3/ **A. Claudi, R. Malewski**, ’Checking of Digital Impulse Analysing Systems against Electromagnetic Interference’, paper 4551, 9 th International Symposium on High Voltage Engineering, Graz, Austria, 24.8.-1.9.1995.

Discussion

G. Prakash, DGM, BHEL Bhopal

1.) What is the limiting noise level in terms of a low coherence function, above which grounding and shielding should be improved?

The coherence function provides an indication of the areas where the ingress of noise made the signal processing not reliable. The coherence function is derived from all the time domain records used in the transfer function calculation. Assuming a linear behaviour of the examined winding, and an ideal, noise-free measuring system, the coherence shall be equal to unity over all the analysed frequency band.

A coherence function value lower than one indicates noise from interference or quantization or a winding fault. There is no certain level of the coherence value below which grounding and shielding has to be improved. However, if little noise and interference are present in your measuring circuit then a more detailed analysis, generally up to a higher frequency range, is possible.

With the coherence check, the impulse measuring circuit can be qualified regarding the frequency range and the dynamic performance of the impulse measuring system. The advantage of this method against others is that the whole measuring circuit is qualified during a „life test". This means that all components contributing to the measurement performance are taken into account, e.g. test object, high voltage connections, divider, low voltage connections, earthing and the digitizer. On the other hand the electromagnetic interference is in the same magnitude as in the real test. So, interference penetrating the measuring circuit will show up in the coherence analysis leading to lower coherence values.

2.) Locating of faults in windings: does the transfer function method of impulse analysing system offer any specific package / guidance for locating faults during SI / LI tests on transformer / reactor windings?

So far no such package exists but there have been several papers published on this topic. One of them is an Indian paper presented at ISH 97 in Montreal (N. Prabhakar et al, Sensitivity Analysis of the Power Transformer Windings by Transfer Function Method). Their conclusion: "...Frequency sensitivity of the windings is less and hence it may be difficult to locate the position of fault in the winding. ..." Possibly new improved analysis software and impulse analysing system of the highest performance class might bring us closer to such a goal.

K. Vijayan, Cromton Greaves LTD

1.) How to distinguish noise from fault indication during LI and SI impulse test, when using highly sensitive digital oscilloscopes.

2.) What measurements are to be taken to eliminate noise pickup on the test circuit especially when using highly sensitive digital oscilloscopes.

This can be done with the coherence check. If transfer functions are different in a range where the coherence function is close or equal to 1 then this indicates a difference in the test object. On the other hand, a small coherence value indicates that the transfer function is doubtful and no serious statement about where differences in transfer functions originate from can be made.

With this test, the impulse measuring circuit can be qualified regarding the frequency range and the dynamic performance of the impulse measuring system. The advantage of this method against others is that the whole measuring circuit is qualified during a „life test". This means that all components contributing to the measurement performance are taken into account, e.g. test object, high voltage connections, divider, low voltage connections, earthing and the digitiser. On the other hand the electromagnetic interference is in the same magnitude as in the real test. So, interference and noise penetrating the measuring circuit will show up in the coherence analysis leading to lower coherence values.

To perform this test, three (or more) voltage and current curve sets should be recorded at a reduced test voltage level including the test object. The voltage level should be adjusted such that it is high enough to produce electromagnetic fields in the same magnitude as in the real test. On the other hand, the voltage should be sufficiently low such that an insulation failure or overstressing of the insulation can be avoided. Practical values range between 40% to 70% of the test voltage. The standard lightning impulse is normally chosen for this test.

L. Satish, Bangalore

1.) Can you please show us how the coherence function will look like, when both full wave and chopped wave data are combined.

With perfect test conditions and measurement instruments both should look the same. However, chopped waves contain far more high frequency components than full waves. Therefore the coherence values obtained with chopped waves are generally close to unity up to higher frequencies. Reasons include the dynamic resolution of the measuring system, interference and noise.

2.) The coherence function is very sensitive and also depends on the procedure that is adopted to compute it. Therefore, can you pleas tell us what procedure you have used?

Computing of the coherence function is not the crucial point as it is basically a straight forward calculation (please consider the paper for exact formalism). The operation which requires closer scrutiny is calculation of the transfer function i.e. the FFT (Fast Fourier Analysis). Many factors such as the kind of windowing performed and zero padding will have a large influence upon the results obtained. In terms of windowing, the use of exponential windows has shown good results.

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