CHECKING ELECTROMAGNETIC COMPATIBILITY OF A HV IMPULSE MEASURING CIRCUIT WITH COHERENCE FUNCTION

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1. ABSTRACT

Over the years digital signal processing has become an accepted tool in evaluation of HV impulse tests, particularly in assessment of tests of non-self restoring insulation, such as in power transformers and reactors.

It has been reported that certain HV test stations have encountered difficulties when their traditional analogue oscilloscopes have been directly replaced by a specialized digital recorder. In most cases the problem has been caused by electromagnetic interference penetrating to the low voltage circuit of impulse voltage divider and shunt , or by the transient ground potential rise over the ground floor impedance.

These difficulties can be eliminated, as soon as their specific nature and location are known. A convenient technique for checking the electromagnetic compatibility of a HV impulse measuring system has been developed, and consists of the calculation of coherence of a few sets of the impulse voltage and output current from the test object.

The coherence reveals frequency intervals where the interference has ingressed the measuring circuit and masked the recorded signals. With the coherence graph overplotted on the transfer function of the test object, the latter can be qualified. The crucial difference between the transfer functions, measured at the full and reduced test voltage levels, can be assessed as genuine, i.e. caused by the insulation fault or partial discharge, or just caused by interference coupled to the measuring circuit.

Examples of transformer impulse test records corrupted by electromagnetic interference as well as by the quantization noise of the digitizer are presented and compared to the records taken in "noise free " environment.

2. INTRODUCTION

Signal processing of digital recorded impulse test data enhances the quality control of high voltage equipment like transformers, reactors or HV-bushings. To qualify a non-self restoring insulation the comparison method has been introduced. For transformer testing a comparison between a reduced impulse and a full impulse reveals internal insulation failures. The conventional method was to compare the voltage on photos taken by an impulse oscilloscope. With a High Resolution Impulse Analysing System (HIAS) the recorded and digitized wave forms can be scaled to the same magnitude, and the time origin can be shifted in a way to minimize 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 (Malewski, Poulin[1]), (Gockenbach, Claudi [2]).

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.

To overcome these problems the so called transfer function has been introduced (Malewski, et al[3]). The transfer function is calculated as the quotient of the neutral current spectrum and the test test voltage spectrum. It reflects 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.

In practise the two obtained transfer functions of the full and reduced levels are superimposed. Neither the amplitude nor the shape of the generated wave form affect the shape of the transfer function. In other words the transfer function shows a fingerprint of the test object which is independent of the generated wave form. In practise some effects influence the performance of this method.

The quantization errors of the digital converter and its limited dynamic resolution limits the upper frequency of the transfer function. But even with an ideal digitizer with e.g. an infinite sampling rate one has to take into account that the voltage and current measuring channels include also a HV divider and a current shunt. These effectively delimit the upper frequency of the channel bandwidth. A comparison of the bandwidth of different components of the measuring system is shown in Fig 1.

Also 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 modern transformers are 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 recognized by experienced inspectors and there is little chance to take such symptoms for an internal breakdown or partial discharge.

The transfer function reveals a local breakdown as a change of a resonant pole, and that change occurs at a given frequency. The ratio of the affected pole magnitude to the adjacent transfer function values is relatively high, since all energy of the difference signal is concentrated in a narrow frequency band around the affected pole.

Hence, 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.

The electromagnetic noise is the main factor which imposes limits on the high voltage measurement and on the practical use of the transfer function.

3. ELECTROMAGNETIC INTERFERENCE IN HV IMPULSE TEST LABORATORY

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 Fig 2.

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

$$I_C = C_g * \Delta U/\Delta t$$

with:

$C_g \sim 2$ [nF] - ground capacitance of the impulse generator top electrode,
$U \sim 2$ [MV] - impulse peak voltage,
$\Delta t \sim 0.1$ [μs] - rise time of the top electrode potential in this example I_c has a value of 40 kA.

It is to be noted that the top electrode rise time may be much faster than the impulse front time, where the generator is equipped with an external front resistor.

In addition, a discharge current of the impulse generator is injected into the grounding mesh at the chopping gap grounding point, and at the tested transformer grounding.

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.

3.1 Conducted Interference

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

A voltage drop U_c developed by the cable shield current I_c across the cable shield resistance R_{sh} represents the conducted interference, which is superimposed on the recorded signal U_s, as presented in Fig 3. 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 U_c: the first calls for selection of a high quality coaxial cable, which is characterized by a low resistance of the cable shield. The second method consists in a reduction of the cable current I_c, 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 I_c up to four times, with respect to a non-magnetic, eg copper pipe.

3.2 Induced Interference

Firing of a HV impulse generator induces an electric and magnetic field component, which attain ~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 the 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.

Design of the shielding structure is dictated by an acceptable level of interference voltage or current induced in the sensitive electronic circuitry. An interference current induced in a typical circuit board of 0.1 m^2 area by the capacitive coupling to the HV impulse generator top electrode has been shown in Fig 4, which illustrates the coupling mechanism.

Assuming the electric field $E \approx 40$ kV/m, and the rise time of the impulse generator top electrode potential $\Delta t \approx 0.1$ μs, the current injected into the circuit board of an area $A=0.1$ m² will attain:

$$i=\Delta Q/\Delta t=\varepsilon_0 * A * \Delta E/\Delta t=0.4 \text{ [A]},$$

where:

Q charge injected into the circuit board,
ε_0 =8.86e -12 [F/m].

An operation of a memory or logic circuit board would be hampered by injection of such an impulse current. A shielding structure is needed to reduce the capacitive coupling to the circuit board by approximately -60 dB. The injected current will be then reduced to 400 μA, a tolerable value for most practical electronic circuits.

A chopping of the lightning impulse, and to same extend also firing of the impulse generator, results in a rapid discharge of the generator stage capacitors, as it is shown schematically in Fig 5. An oscillatory current circulating in an LC circuit composed of the generator capacitance $C \approx 2$ nF and inductance $L \approx 100$ μH of the discharge circuit, may attain:

$$I_{max} \approx 0.7 * U/\sqrt{L/C} \approx 50 \text{ [kA]},$$

and the fundamental frequency of this oscillation is:

$$f=1/2\pi\sqrt{LC} \approx 50 \text{ [kHz]}.$$

An initial rate of rise of this current:

$$|\Delta I/\Delta t|_{max}=U/L=2*10^{10} \text{ [A/s]}.$$

and

$$\Delta t \approx I_{max}/|\Delta I/\Delta t|_{max} = 2.5 \text{ [μs]}.$$

The resulting magnetic field H=1000[A/m] will induce an interference voltage U_{ind} in the circuit board of an area A=0.1 m²:

$$U_{ind} \approx \mu_0 * A * \Delta H/\Delta t=64 \text{ [V]},$$

or

$$U_{ind} \approx \mu_0 * A * 2\pi f * H=40 \text{ [V]}.$$

Again, such an impulse induced in a electronic or logic circuit will interfere with its operation, and an electromagnetic shield is required to ensure reliable functioning of the recorder or computer.

Shielding efficiency of -50 to -60 dB is needed to reduce the induced voltage down to a tolerable level of 100 μV.

3.3 Electromagnetic Shielding Structures

Let us consider a high frequency magnetic field component impinging on a cube-formed box made of a continuous copper sheet, and welded along all joints. A high frequency current will be induced in the box walls in such a way to produce a magnetic field opposing the externally applied interference field.

A perfect cancellation of the applied field would be achieved if the box were made of a superconductive material. Resistance of the copper sheet, although low, will result in dissipation of a certain loss, and the current induced in the box walls will be slightly lower than that needed for the perfect shielding. In consequence, a part (H_{ind}) of the applied field (H_{app}) will enter inside the box. The shielding efficiency SE of this structure is given by:

$$SE=20*\log_{10}(H_{ind}/H_{app}).$$

In the real world. a shielding structure shall have openings for installation of instruments, ventilation, and entrance of cables. All these cut-outs deviate the current flow in the box walls, and may let the applied field to penetrate inside the shielded enclosure. To minimize the influence of doors on the shielding efficiency, a special joint material, or gasket is employed. The main feature of such "electromagnetic gasket" is a very good electric contact between the door rim and the frame. A high conductivity of this contact has to be maintained even if the potential difference across the joint is as low as a few microvolts. At this stage, it should be kept in mind that even a thin layer of oxidation or grease is quite sufficient to prevent a uniform flow of the induced current through the joint.

Certain makes of these joints are gold plated to eliminate oxidation, some other are made of hard beryllium-copper alloy in form of elastic "fingers" which scratch the adjacent door panel and renew the good electric contact at each closing and opening of the door.

Shielding structures made of separate side panels have to be welded to ensure the required good contact between adjacent panels. As an alternative, commercially available seams can be used. These have been designed to maintain a high conductivity electric contact between permanently bonded panels.

A high quality electromagnetic shield for use in the HV impulse test laboratory should be characterized by shielding efficiency of 70 to 80 dB for the electric, and 50 to 60 dB for magnetic field component. This shielding efficiency should be maintained at least up to a few megahertz.

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

4. CHECK FOR COHERENCE OF THE RECORDED SIGNALS

The problem of noise imposed on measured quantities has been extensively studied also in other fields, and successful signal processing methods to assess the influence of noise have been first implemented in acoustic measurements. One of them, referred to as 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 analyzed frequency band.

The coherence function γ^2 is calculated as a quotient of the cross-correlations $|G_{xy}|^2$ and autocorrelation of the applied voltage G_{xx} times autocorrelation of the neutral terminal current G_{yy}.

$$\gamma^2 = |G_{xy}|^2 / G_{xx} * G_{yy};$$

where:

$$G_{xx}=\Sigma|U|^2/n, \quad G_{yy}=\Sigma|I|^2/n, \quad \text{and} \quad G_{xy}=\Sigma|U^*I|/n.$$

In this expression U denotes the frequency spectrum of the recorded voltage, U* its complex conjugate, I is the neutral terminal current spectrum and n the number of sets. An example of different records is shown in Fig 6. In this example n=3. The cross correlation of three test records is presented in Fig 7, and their coherence in Fig 8. The graph reveals a gradual reduction of coherence above ~1.5 MHz, where the transfer function shows major differences.

In this example the measuring circuit has been properly shielded against the electromagnetic interference.

and the digital recorder quantization noise has been the predominant source of error.

However in many practical situations a transient electromagnetic interference can enter the measuring circuit at the divider low voltage arm, or penetrate through the coaxial cable sheath and the digital recorder enclosure. Ideally, all these devices shall be protected by a perfect electromagnetic shield, but in reality its shielding efficiency decreases with frequency.

In consequence, high frequency components of the transient interference field can penetrate the measuring circuit with lesser attenuation. They may effectively mask the measured signal spectrum at much lower frequency than the limit imposed by the digitizer quantization noise. Usual precautions taken to reduce the interference in the conventional, analogue HV impulse measuring circuit are not sufficient to ensure an error free digital recording and processing of HV transients.

Another example is presented in Fig 9. The transfer functions of 3 recorded impulses show some differences above 1.2 MHz. Without knowing the limits of the measuring system this would certainly lead to some discussion regarding the quality of the test object, here a 735 kV, 150 MVA transformer. The coherence function clearly shows up that above 1.2 MHz the quantization noise of the digital recorder is the predominant source of error. Any calculations above that frequency are not reliable.

A measuring circuit with a poor shielding and insufficient bandwith is shown in Fig 10. Clearly visible some noise penetrated the signal even at low frequencies around 100 kHz. The frequency limit of that circuit lies around 700 kHz.

From the practical point of view, the low coherence shall be considered as a warning. This warning tells the user that he has to improve his grounding and shielding system, if the coherence is low below the frequency at which the quantization noise starts to mask the spectrum of digitally recorded signals.

5. REFERENCES

1. Malewski R, Poulin B: 'Digital Monitoring Technique for HV Impulse Test', IEEE PES Winter Meeting, New York, USA, paper 85 WM 116-9.

2. Gockenbach E, Claudi A: 'The Digital HV Impulse Measuring System: A New Tool For Diagnosis and Automation', Proceedings of the Conference: International Symposium on Digital Techniques in High Voltage Measurements, Toronto, Canada, 1991, pp 3.23-3.27.

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

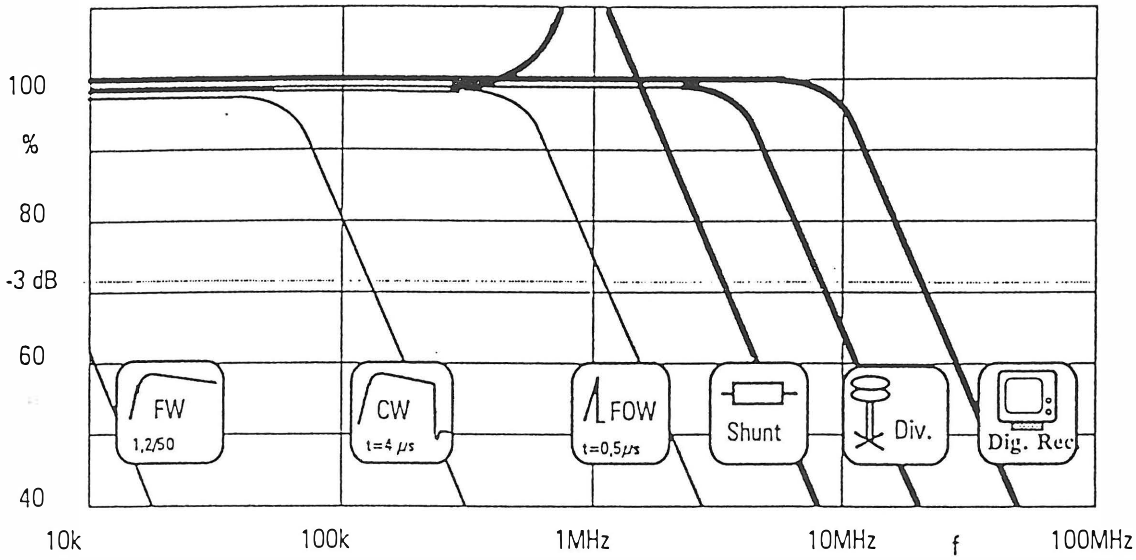

Fig 1 Bandwidth and spectra of different measuring devices and test impulses. FW full wave lightning impulse 1.2 µs / 50 µs, CW chopped wave (chopping time 4 µs), FOW front chopped wave (chopping time 0.5 µs), Shunt typical HV measuring coaxial shunt, Div. typical HV capacitive damped impulse divider, Dig. Rec. typical HV digital recorder (HIAS).

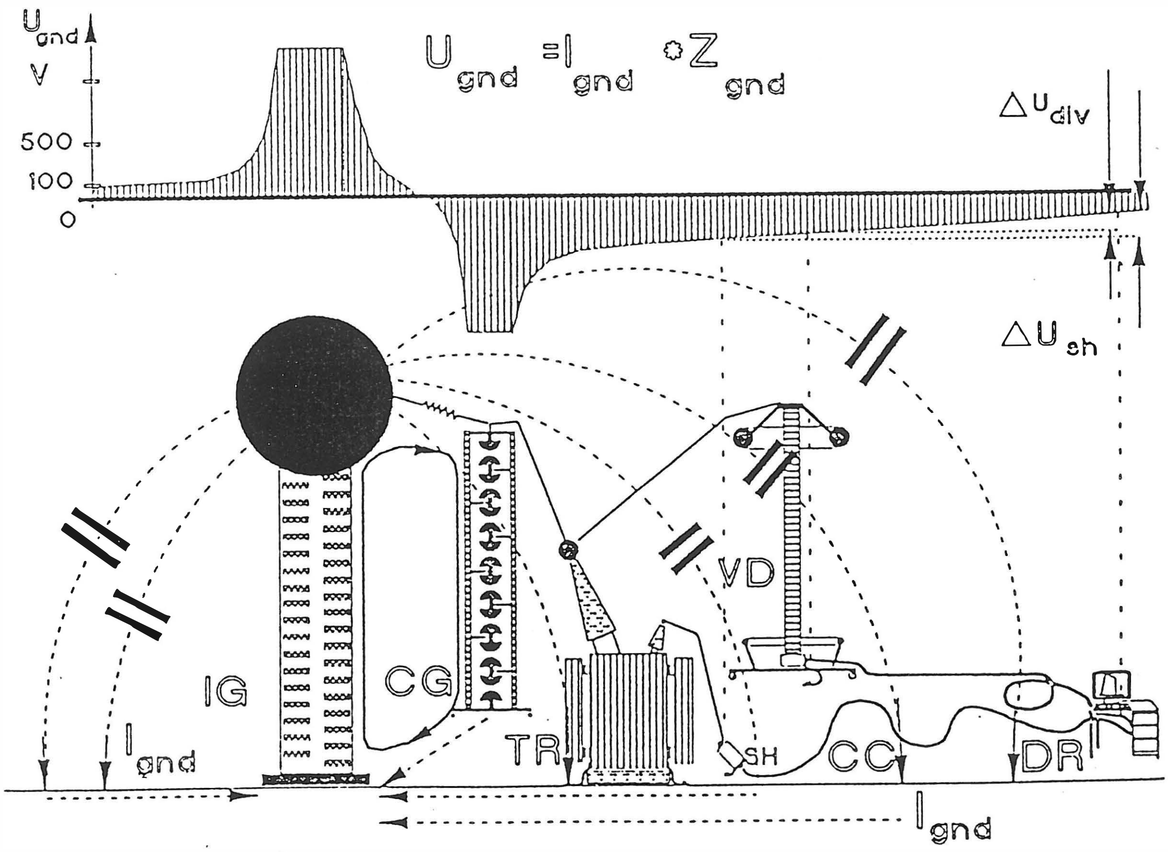

Fig 2 HV impulse test set up. IG impulse generator, CG chopping gap, TR transformer under test, VD voltage divider, SH current measuring shunt, DR digital recorder, CC coaxial cable, U_{gnd} voltage drop on the ground mesh impedance, I_{gnd} capacitive current collected by the ground mesh, ΔU_{div} and ΔU_{sh} potential difference between an input end of the voltage divider and shunt cable.

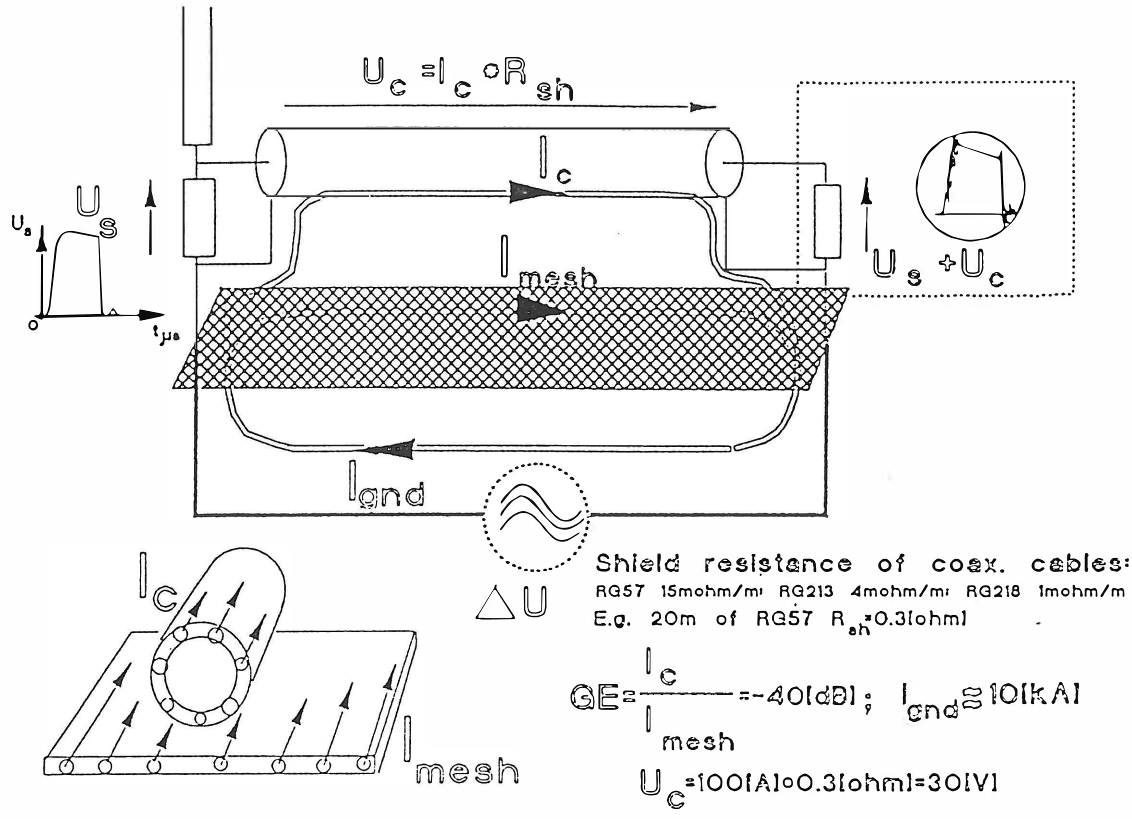

Fig 3 Repartition of the ground current between the ground mesh I_{mesh}, and the coaxial cable shield current I_C. A conducted interference U_C corresponding to the voltage drop on the coaxial cable shield resistance R_{sh} due to a part of the ground I_C flowing in this shield $U_C=I_C*R_{sh}$.

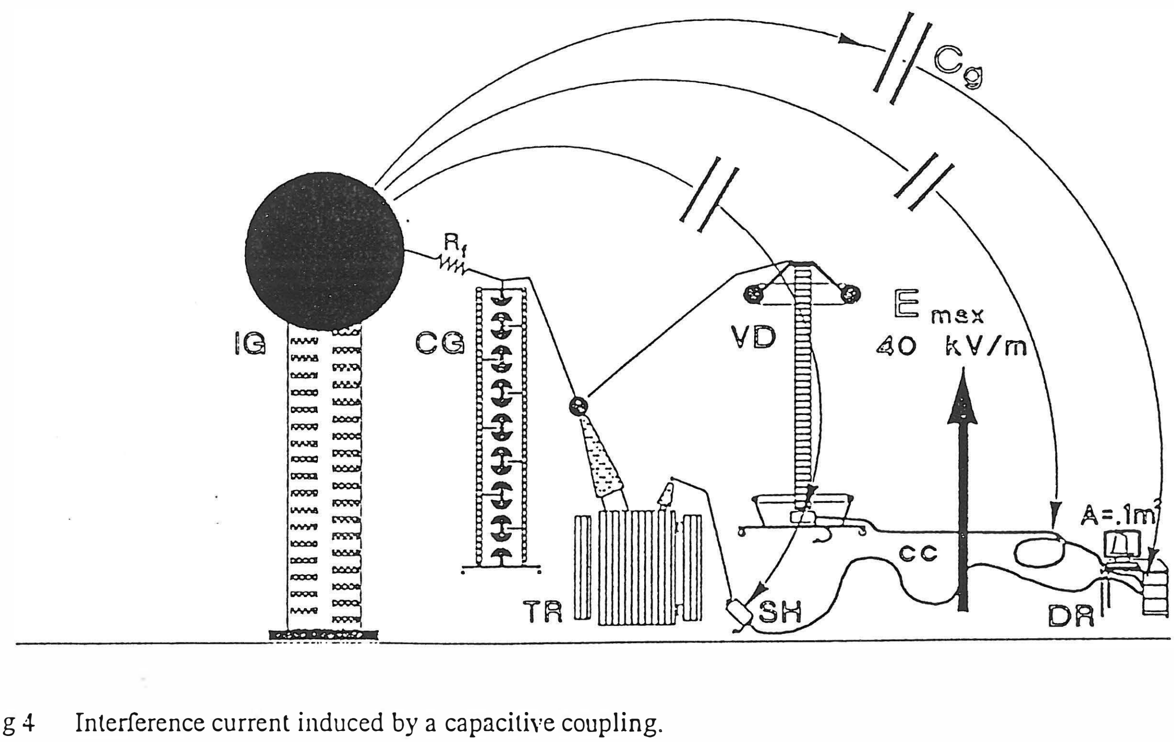

Fig 4 Interference current induced by a capacitive coupling.

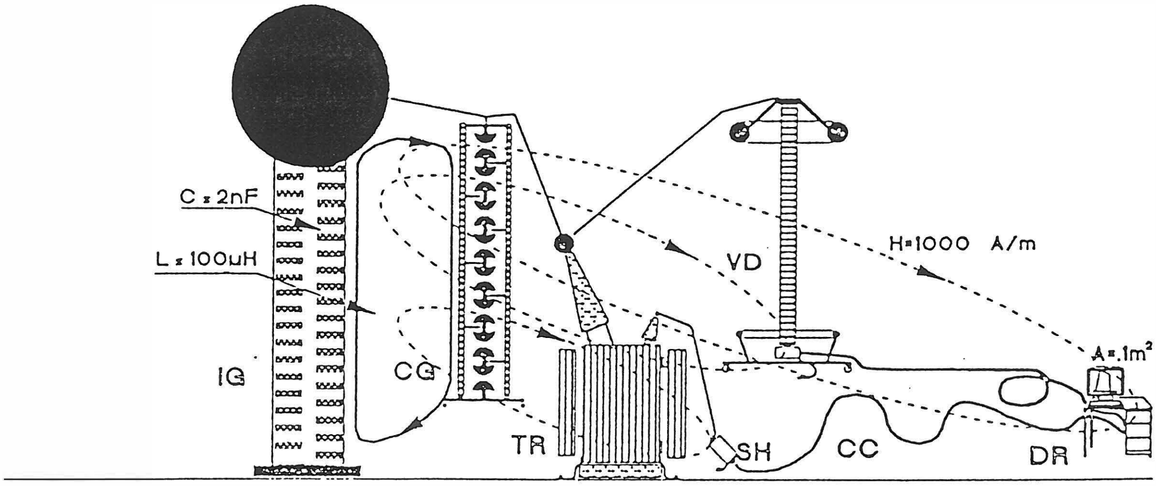

Fig 5 A discharge of the impulse generator capacitance through the chopping gap (or the test object) results in an oscillatory current, which circulates in the discharge path loop. A magnetic field induced by this current impinges on the recording instrumentation. This magnetic field H induces, in turn, an interference voltage U_{ind} in an electronic circuit of the digital impulse recorder. This voltage attains ~50 V in a board of A=0.1 m² area.

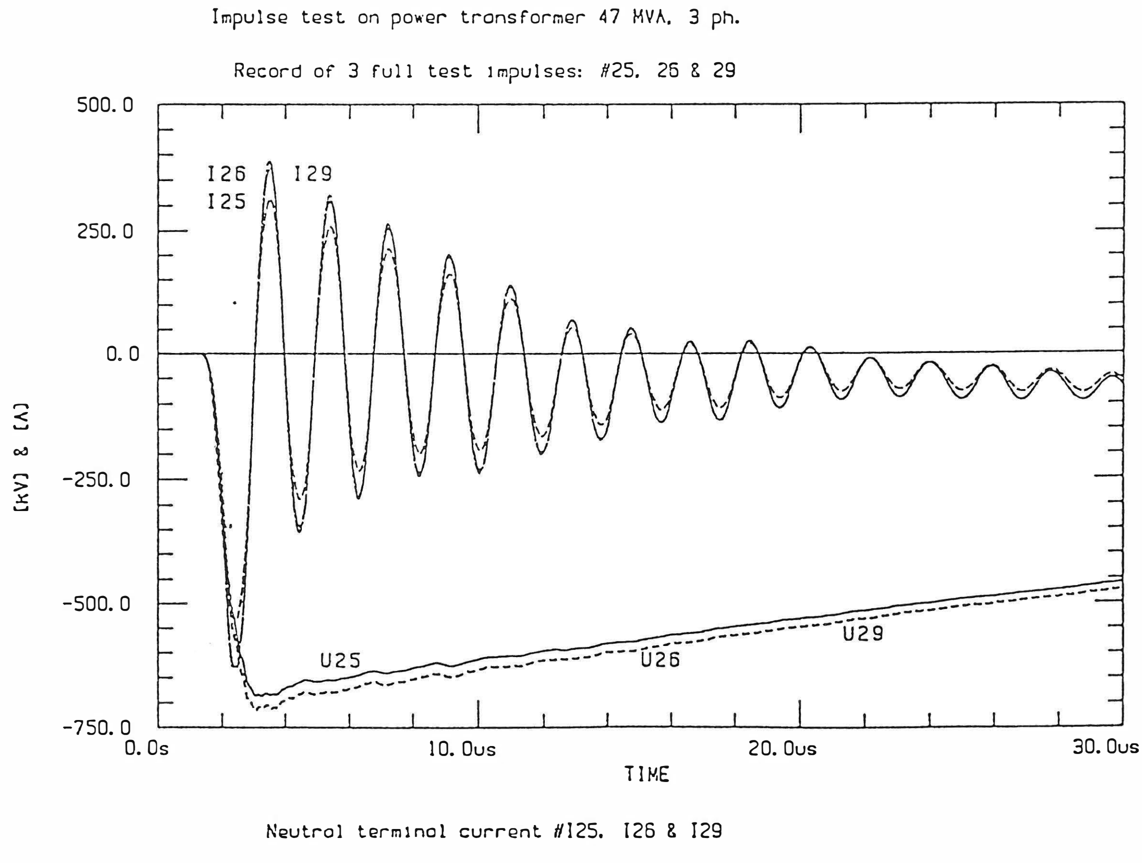

Fig 6 Three records of full and reduced level test voltage and neutral current.

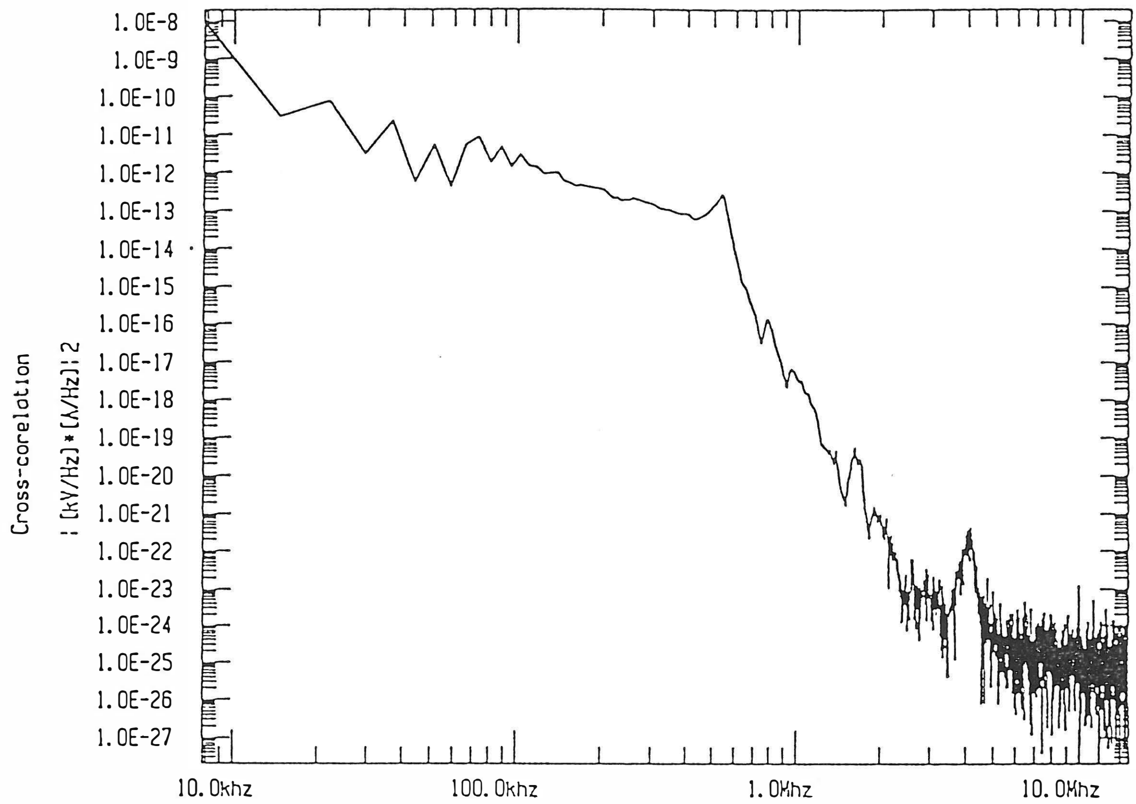

Fig 7 Cross correlation of the voltage and current records.

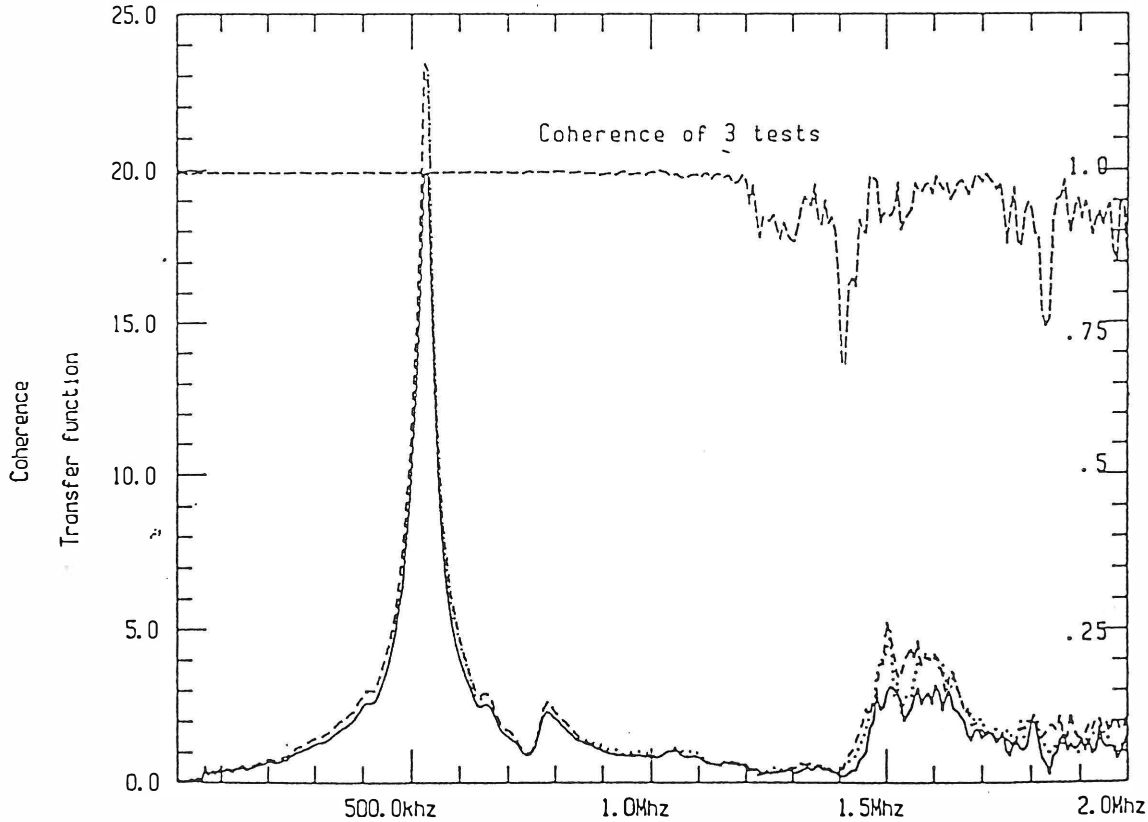

Fig 8 The transfer function calculated from the three sets of records.

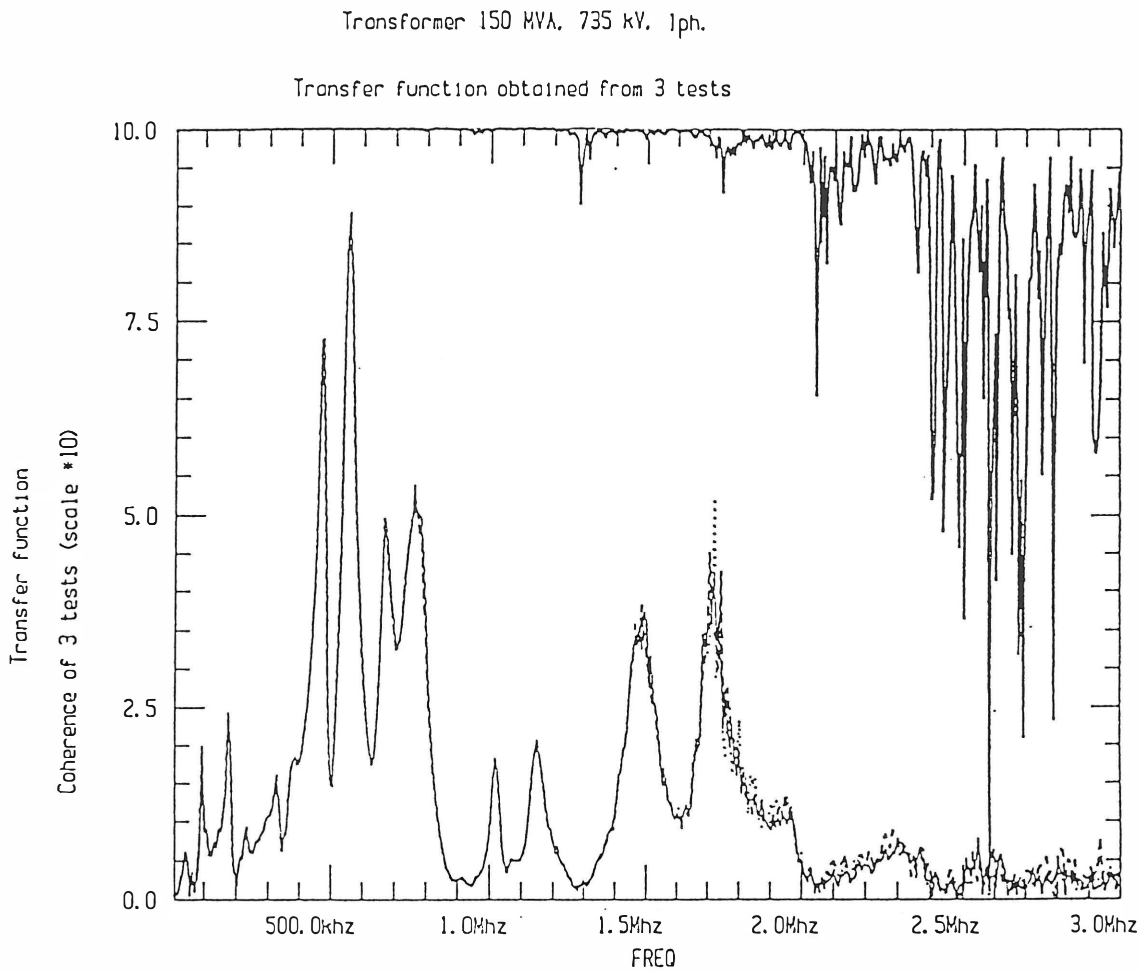

Fig 9 Transfer and coherence function of a 150 MVA transformer, 735 kV, 1 phase.

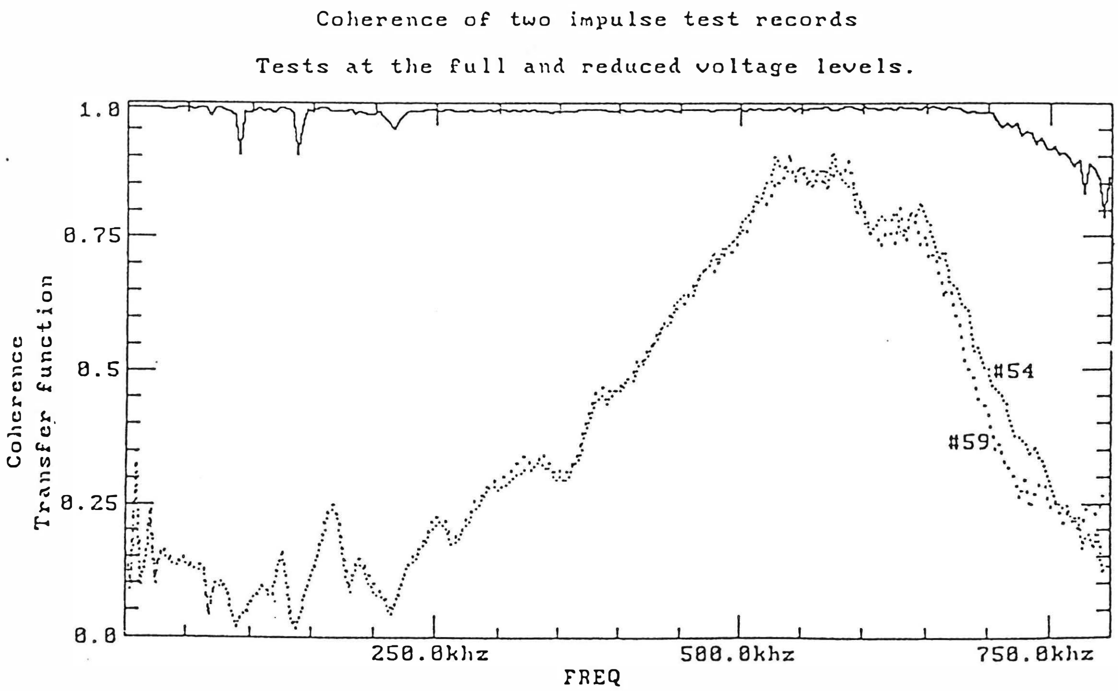

Fig 10 Transfer function calculated from the voltage and current recorded at the terminal X.