

**DIGITAL TECHNIQUE FOR
ON-LINE MEASUREMENT OF DISSIPATION FACTOR
OF HIGH VOLTAGE APPARATUS**

by
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A Thesis
Submitted to the Faculty of Graduate Studies
in partial fulfillment of the requirements
for the degree of
Master of Science

**Department of Electrical and Computer Engineering
University of Manitoba
Winnipeg, Manitoba**

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ZHENGKAO ZHANG

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
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MASTER OF SCIENCE

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Abstract

To ensure the reliability of power supply it becomes necessary to periodically monitor the condition of power apparatus. Conventionally this may be achieved by carrying out tests such as the partial discharge and dissipation factor tests in a laboratory. This method, however, requires that the apparatus in question be disconnected from service and transported to the testing location. In the last few years on-line diagnostic tests have found favour not only because they are cost effective but also do not involve service interruption and furthermore offer the possibility of continuous monitoring.

The reported methods measure the phase difference between voltage and current digitally by converting the signals to rectangular waveforms while preserving zero crossings. The method discussed in this paper uses a different technique. The Discrete Fourier Transform (DFT) is performed on the acquired analog signals; the phase difference is found from phase information of the fundamental quantities. This procedure effectively eliminates errors due to harmonics. It has an additional advantage in that the error introduced due to noisy data is smaller than that present in a method which relies on detection of zero crossings.

The suggested method has been validated by comparison with the results obtained by a conventional bridge measurement. The effects of sampling rate and system frequency fluctuation on the measurement have also been studied.

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CHAPTER 1

INTRODUCTION

With increasing time in service, the quality of the insulation of high voltage apparatus deteriorates and the risk of insulation failure increases. Monitoring the condition of apparatus insulation at service voltage is therefore necessary in order to maintain the reliability of electric power supply. This may be accomplished by disconnecting the apparatus from system and transporting it to a laboratory and measuring the dissipation factor, partial discharge level or other quantities by using conventional methods. However, this technique is not only labour intensive but also introduces service interruption. It may be mentioned that Manitoba Hydro conducts tests on some high voltage apparatus in situ, after disconnection from service, at a reduced voltage of 12kV using a current comparator.

On-line diagnostic methods, on the other hand, can be implemented, at service voltage, without service interruption. They are receiving increased attention because they are not only more economical but also offer the possibility of continuous monitoring of the equipment under system voltage and operating conditions. On-line methods have been developed to monitor partial discharges and dissipation factor in the insulation of high voltage apparatus [1]. Continuous monitoring of insulation dissipation factor and partial discharge levels makes it possible to set up an “intelligent” system which can assess the condition of insulation and suggest timely remedial action.

1.1 Review of conventional methods

The well-known conventional methods are:

- Dissipation factor measurement ($\tan\delta$)
- Partial discharge measurement (PD)
- Recovery voltage method
- Insulation resistance measurement
- Dissolved gas analysis (DGA)

Implementation of the first two techniques may necessitate the test object to be disconnected from the power system and transported to the laboratory for test. The next two techniques can be implemented on site. In some cases DGA can be carried out by transportation of samples to the laboratory for analysis (sampling of bushings and instrument transformers is difficult).

1.1.1 Dissipation factor measurement

The measurement of dissipation factor is based on the assumption that the insulation can be electrically modeled as a lossy capacitor. An ideal insulation with a perfect dielectric may be represented by a lossless capacitor. Thus in the latter case, under AC excitation, the phase shift between applied voltage and current (called power factor angle) will be exactly 90° . In practical insulation, losses arise due to leakage, voids and polarization; the power factor angle is less than 90° . The complement of the power factor angle is known as loss angle; its tangent is referred to as dissipation factor, i.e. $\tan\delta$. Practical insulation may be represented by either a series or parallel combination of resistance and capacitance.

One of the most commonly used methods for measuring dissipation factor is the Schering bridge [2] which is shown in Fig 1.1. The bridge measures the dissipation factor and also the capacitance by comparison of the test specimen with a gas-filled standard capacitor which has negligible loss.

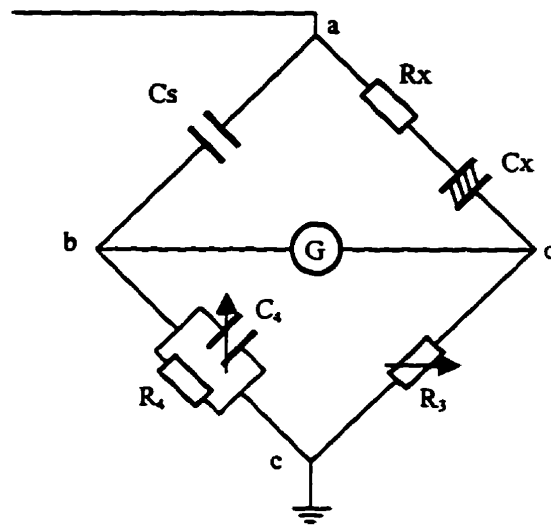


Fig 1.1: Schering bridge

The balance conditions obtained when the indicator shows zero deflection in Fig 1.1 are:

$$\frac{Z_{ab}}{Z_{bc}} = \frac{Z_{ad}}{Z_{dc}} \quad (1.1)$$

$$\text{from Eq(1.1)} \quad \tan \delta = \omega C_x R_x = \omega C_4 R_4 \quad (1.2)$$

Another type of bridge used for dissipation factor measurement is the current comparator bridge [3] which is shown in Fig 1.2. Such a bridge has transformer windings with adjustable taps for two of its arms and the detector is connected to a

third winding on the core. Zero net flux in the core is used as the balance condition. This bridge provides even more accurate measurements than that possible with a Schering bridge.

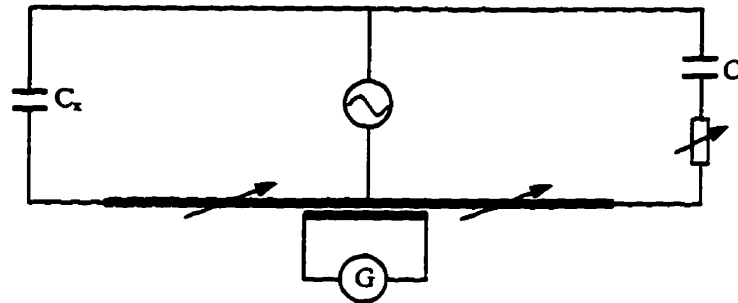


Fig 1.2: Current comparator bridge

Reference [4] describes a method for the on-site measurement of dissipation factor and capacitance using a low voltage Schering bridge. The test object C_x is energized by the system bus and the low voltage portable standard capacitor C_s is energized by the secondary of a P.T. connected to the same bus. Stray influences, the effects of losses in the standard capacitor and P.T. and the influence of ground leads must be taken into account, in order to obtain an accurate value for the dissipation factor. The layout of the measuring circuit is shown in Fig 1.3.

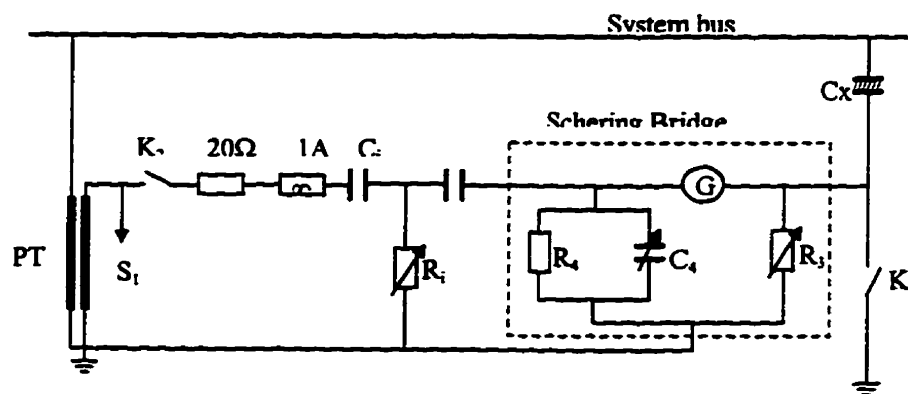


Fig 1.3: Test circuit for measuring $\tan\delta$ using Schring bridge

In Fig 1.3, S_1 is the normal secondary load of PT. The 20Ω resistor and the 1A fuse are safe guards against accidental short circuit of the secondary of the PT. C_i and R_i form a RC divider. The expression for dissipation factor is as follows,

$$\tan \delta_x = \tan \delta_r + \omega C_i R_4 - \tan \gamma - \frac{1}{\omega C_i R_i} + \omega C_4 R_4 \quad (1.3)$$

where γ is the phase angle error of PT. If R_i is selected such that

$$\frac{1}{\omega C_i R_i} = \tan \delta_r + \omega C_i R_4 - \tan \gamma \quad (1.4)$$

Eq(1.3) simplifies to

$$\tan \delta_x = \omega C_4 R_4 \quad (1.5)$$

Eq(1.5) is of the same form as Eq(1.2), the balance equation for a Schreing bridge.

1.1.2 Partial discharge measurement

Partial discharges are localized electrical discharges within an insulation system, restricted to only a part of the dielectric material. They include both internal and surface discharges. The occurrence of internal discharges in cavities deteriorates the material due to the energy impact of high-energy electrons or accelerated ions, which cause chemical transformations of many types and deterioration. The occurrence of surface discharges leads to tracking and possible eventual failure.

Different from the dissipation factor measurement which reflects the global condition of a test object, partial discharge testing is concerned with the detection and quantization of discharges in the test object. It is helpful because breakdown is often

initiated due to localized discharge activity.

The detection of discharges is based on the energy exchanges that take place during the discharge. A typical partial discharge measuring circuit and the associated PD elliptical display are shown in Figs 1.4 and 1.5 respectively.

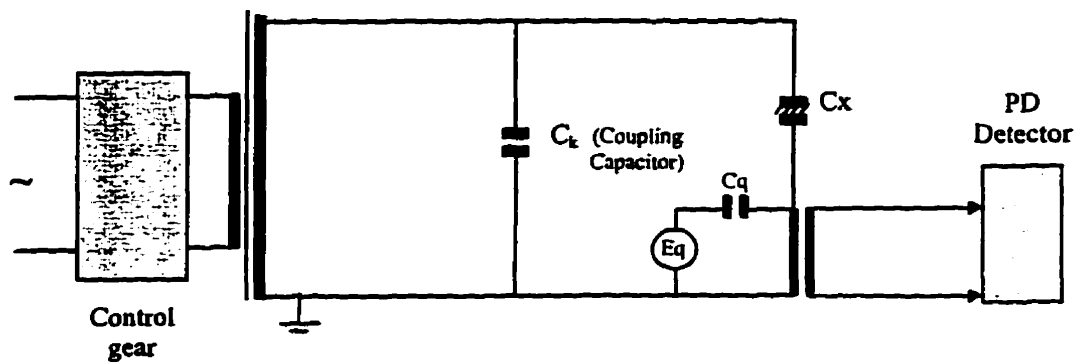


Fig 1.4: Set up for PD test [21]

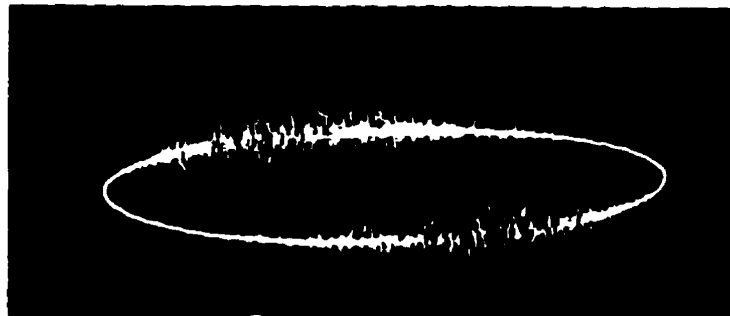


Fig 1.5: PD elliptical display

1.1.3 Dissolved gas analysis (DGA)

For oil and oil-impregnated insulating materials, DGA can play an important role in detecting insulation condition. Oil related insulating materials decompose and

generate decomposition products under the influence of thermal and electrical stress. Different faults within the insulation dissipate different amounts of energy, which results in different distributions of the dissolved gases. By investigating the nature and amount of the individual component gases extracted from the oil using gas chromatographic techniques, the insulation condition as well as the type and degree of the incipient faults can be identified.

The results of a DGA may be analyzed through application of a method known as "Rogers Ratio Method[5]" shown in Table 1.1. Other methods of analysis include the Dormenburg ratio method[6], ANSI/IEEE method[5], LCIE method[7], Laborelec method[7,8].

Table 1.1: Suggested diagnosis from gas ratios according to Roger's ratio method[5]

CH_4/H_2	$\text{C}_2\text{H}_6/\text{CH}_4$	$\text{C}_2\text{H}_4/\text{C}_2\text{H}_6$	$\text{C}_2\text{H}_2/\text{C}_2\text{H}_4$	Suggested Diagnosis
$>0.1, <1.0$	<1.0	<1.0	<0.5	Normal
≤ 0.1	<1.0	<1.0	<0.5	Partial discharge – Corona
≤ 0.1	<1.0	<1.0	≥ 0.5	Partial discharge – Corona with tracking
$>0.1, <1.0$	<1.0	≥ 3.0	≥ 3.0	Continuous discharge
$>0.1, <1.0$	<1.0	≥ 1.0	≥ 0.5	Arc – With power follow through
$>0.1, <1.0$	<1.0	<1.0	$\geq 0.5, <3.0$	Arc – No power follow through
≥ 1.0	<1.0	<1.0	<0.5	Slight overheating – 150°C
≥ 1.0	≥ 1.0	<1.0	<0.5	Overheating – $150\text{-}200^\circ\text{C}$
$>0.1, <1.0$	≥ 1.0	<1.0	<0.5	Overheating – $200\text{-}300^\circ\text{C}$
$>0.1, <1.0$	<1.0	$\geq 1.0, <3.0$	<0.5	General conductor overheating
$\geq 1.0, <3.0$	<1.0	$\geq 1.0, <3.0$	<0.5	Circulating currents in windings
$\geq 1.0, <3.0$	<1.0	≥ 3.0	<0.5	Circulating currents core and tank; overloaded joints



The results of such analysis are not always clear-cut, but may yield a basis for arriving at a decision concerning remedial action.

1.1.4 Recovery voltage method

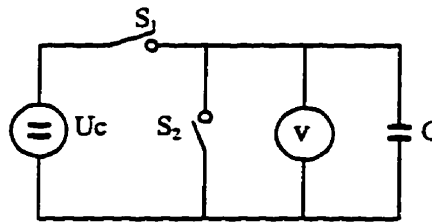
The recovery voltage method has been used to detect moisture in paper and water trees in XLPE cables. It is based on polarization theory. Upon the application of electric field to a dielectric, two fundamental dielectric processes develop. They are conduction and absorption. Both of them are strongly influenced by aging, deterioration and moisture ingress.

The process of conduction is easily characterized by a single quantity, conductivity or resistivity. However polarization is a more complex phenomenon, a resultant of several elementary processes. It can be characterized by a spectrum involving the distribution of the intensity of the individual processes plotted vs. their time-constants. Each of the elementary polarization processes is related to well-defined kind of charge carriers or dipoles (e.g. ions or molecular-groups). If the density of a certain type of charge carrier changes due to the presence of moisture or aging-deterioration processes in the insulation, the intensity of the corresponding elementary polarization will change as well. The change in the polarization spectrum may be used to indicate the progress of deterioration.

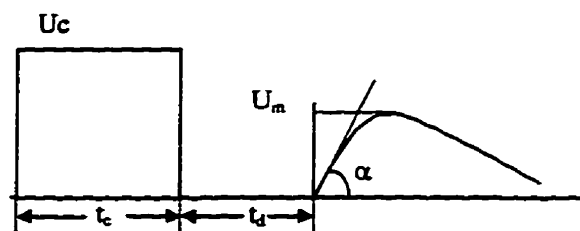
The principle, procedure and interpretation of recovery voltage measurement is shown in Fig 1.6[10]. The insulation tested (represented by a capacitor C) is charged by a DC voltage of magnitude U_c for time t_c by closing switch S_1 ; next, it is isolated from the voltage source by opening S_1 and short-circuited by S_2 for time t_d

(usually $t_d = t_c/2$). Finally, S_2 is switched off and a so-called return voltage gradually appears on the electrodes.

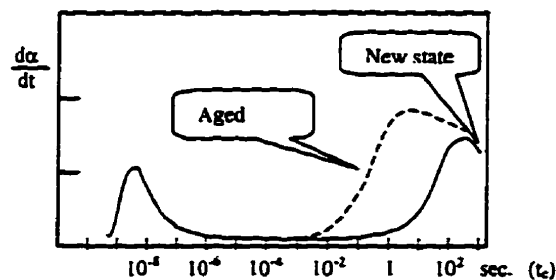
Theoretically it can be proved that the initial slope and the maximum value of the return voltage can indicate insulation aging. In practice, two polarization spectrums can be developed by adjusting the value of t_c , i.e., they are $d\alpha/dt$ vs. $\log t_c$ and U_m/U_c vs. $\log t_c$ (α , U_m are defined in Fig 1.6b). The insulation condition can be ascertained directly from those polarization spectrum curves, as shown in Fig 1.6 c and d.



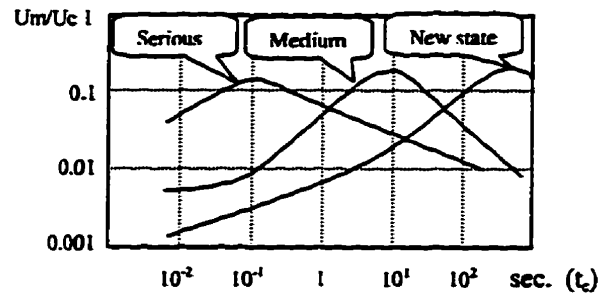
(a) Set up



(b) Measurement procedure



(c) Polarization spectrum of aged insulation
in terms of $d\alpha/dt$



(d) Polarization spectrum of aged insulation
in terms of U_m/U_c

Fig. 1.6: Measurement of return voltage

1.1.5 Insulation resistance

The insulation resistance can be measured using DC voltage. Because of the very high insulation resistance of the measured objects, the measured direct current is very small and of the order of the disturbance current induced in the circuit due to interference fields. In [11], the noise voltage is measured and an opposite polarity voltage is generated in the current to cancel the noise. This cancellation voltage is memorized and introduced in the measuring circuit when necessary.

1.2 On-line Methods

As mentioned above, on-line insulation monitoring methods are gaining popularity because of the advantages they offer. They involve digital signal processing and use a PC to carry out computations. Typically, either the dissipation factor or the partial discharge level or both are measured by capturing and processing the voltage across and the current through the test object which is in service.

Reference [12] describes a method for monitoring the insulation dissipation factor. Fig 1.7a shows the setup and Fig 1.7b the block diagram of measuring system. Here the analog voltage is obtained from the secondary of a PT and a divider; the current signal is obtained from a sampling resistor. The two signals are then processed by a filter to eliminate the effects of noise and harmonics.

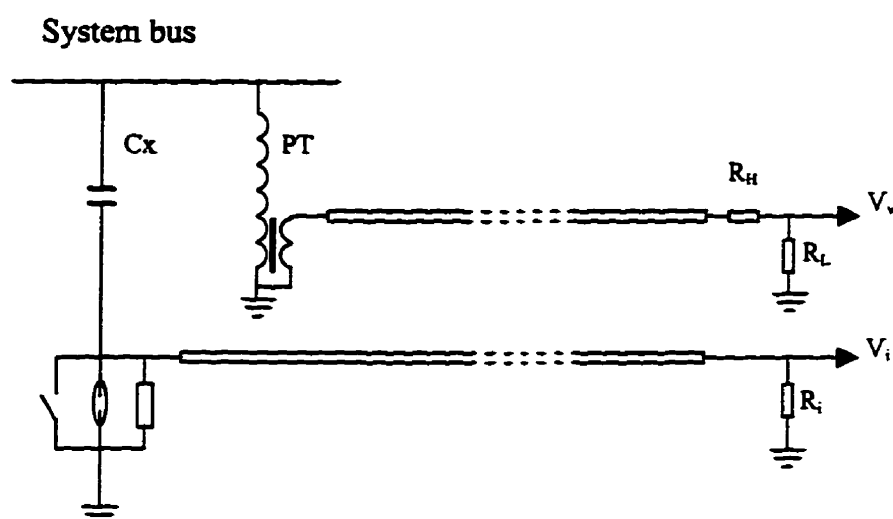
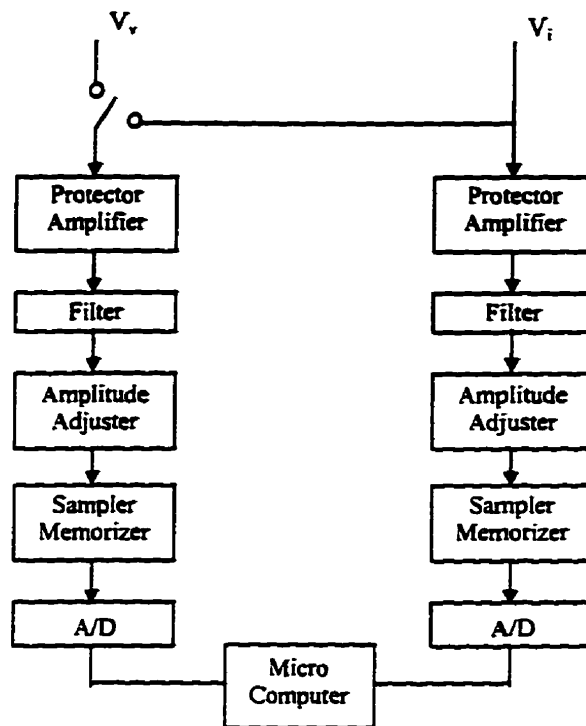


Fig 1.7a: Measurement set-up in [12]

The principle employed in [12] for measuring the dissipation factor is as follows: first, the measured current and voltage signals are converted into rectangular waveforms, as shown in Fig1.8; next the difference pulse is obtained. The width of the difference pulse contains information about the phase difference. This is found by counting the number of clock pulses necessary to account for this pulse width.



(b)

Fig 1.7b: Measurement setup and block diagram in [12]

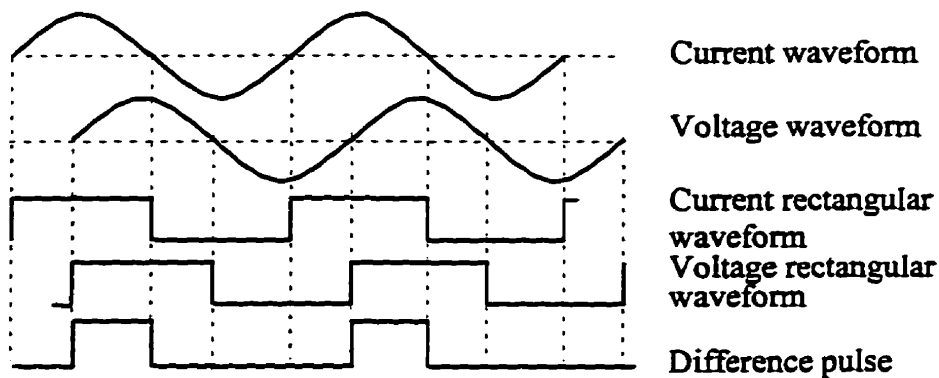


Fig 1.8: Derivation of the difference pulses

A similar technique is used in [13]. The on-line monitoring system is shown in Fig 1.9. Here test capacitors, called caplinks, are inserted at the bottom end of a

capacitive stack and the equipment under test. The former provides a reference power frequency signal. These two signals are used to derive the phase difference between voltage and current. As in [12], the phase difference is obtained by counting the number of clock pulses in the difference pulse.

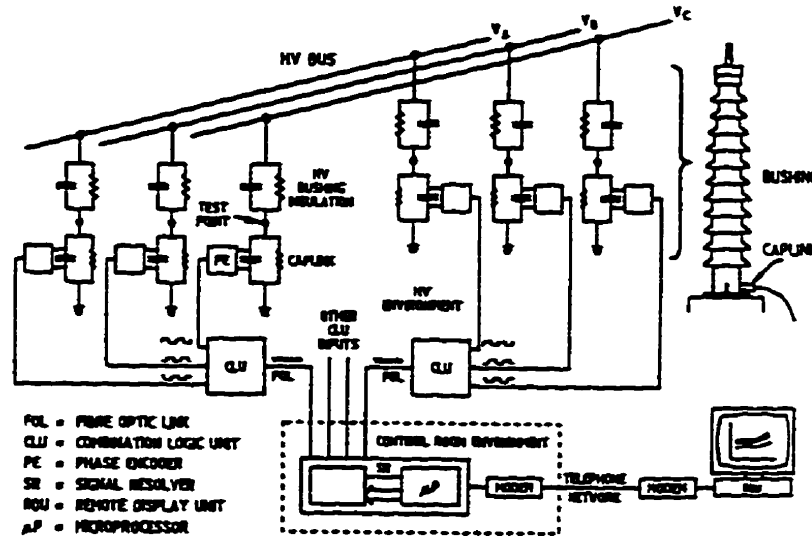


Fig 1.9: An on-line insulation monitoring system[13]

The measurement accuracy of the above methods is mainly dependent on the purity of the acquired signals. In practice, interference and harmonics may be present in the measuring system which contaminates the signals. It is important for the methods to eliminate the effects of noise and harmonics efficiently. Otherwise the zero-crossing points shift with accompanying measurement errors.



1.3 Scope of the present work

The work reported in this thesis is concerned with the digital measurement of $\tan\delta$, dissipation factor of high voltage insulation. The suggested method, which is applicable to on-line testing, uses a different technique. The DFT is performed on the acquired analog voltage and current signals, and the phase difference is found from phase information of the fundamental quantities instead of relying on detection of zero-crossing points. This procedure effectively eliminates errors due to harmonics. It has an additional advantage in that the error introduced due to noisy data is smaller than that present in a method which relies on detection of zero crossings.

In order to validate the suggested method it was applied to measure the dissipation factor in different situations. They are:

- Low voltage validation measurements with a low-loss polystyrene capacitor and a parallel resistor
- High voltage measurements with an artificial cavity
- High voltage measurements with a resin-impregnated capacitor
- Application of different sampling devices (AT-MIO-16F-5 board and TDS-540 digital oscilloscope)
- The effects of sampling rate and system frequency fluctuation on the measurement are also studied



CHAPTER 2

MEASUREMENT SETUP, PROCEDURE AND TECHNIQUES

This chapter describes the measurement principle of the proposed method, the test setup and procedure. The methods employed to eliminate measurement errors are also discussed.

2.1 Measurement principle

The basic principle of the suggested technique is to measure the phase difference between the fundamental components of the applied voltage across and the current flowing through the test object. To accomplish this, as mentioned in Chapter 1, the DFT is performed on the acquired digital signals and the phase difference found from phase information of the fundamental quantities. In order to realize the suggested principle, data acquisition and digital signal processing techniques were employed in the implementation.

2.2 Measurement setup and data acquisition

2.2.1 Data acquisition

The voltage and current signals are in continuous analog forms and require conversion into discrete forms for digital computer processing. This process involves multiple-channel sampling in the time domain, quantization in the amplitude domain,

and coding the resulting information into digital form. Sampling of the analog signal involves the selection of a series of narrow impulses of the signal, spaced at equal time intervals. The data acquisition system used in this project is shown in Fig 2.1.

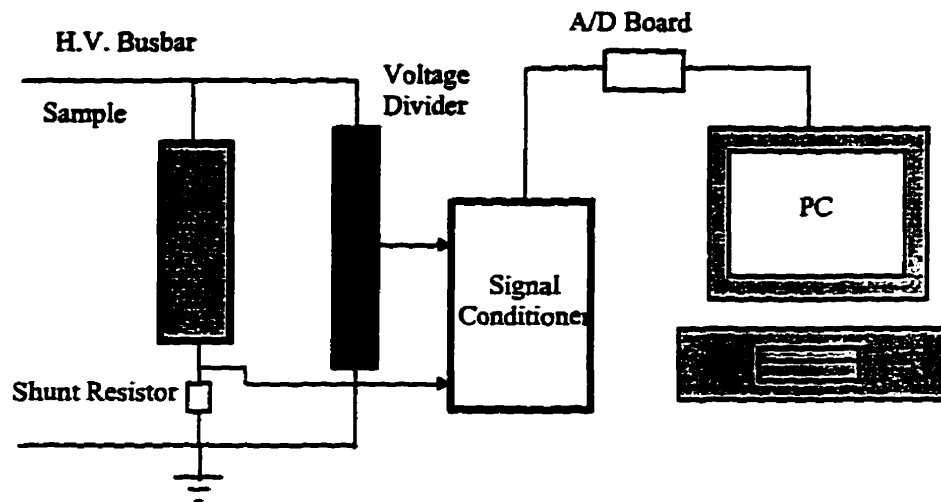


Fig 2.1: Data acquisition system

The voltage signal was derived from a voltage divider and the current signal obtained by measuring the voltage drop across a shunt resistor. This method has advantages over one in which a capacitive element is used. First it is more stable and furthermore the effect of harmonics is enhanced. The acquired voltage and current signals were then passed through a signal conditioner prior to digitization. Finally, developed data acquisition software was used for the dissipation factor calculation.

The hardware and software used for data acquisition are from National Instruments Inc.. The AT-MIO-16F-5 board was used as the hardware to perform A/D conversion. It has a 12-bit sampling A/D converter; the maximum sampling rate is 200ksamples/sec. In this work, two channels (voltage and current) were to be sampled simultaneously therefore the maximum rate for each channel is



100ksamples/sec. The detailed specifications for the AT-MIO-16F-5 board are listed in Appendix A. The LabWindow V2.1 was used to support the A/D board and perform data acquisition and support the measurement program.

2.2.2 Sampling theorem

For a given signal with the highest frequency f , the lowest sampling frequency necessary to preserve the information contained in a sampled version of this signal is given as $f_s = 2f$.

Thus if $f_s \geq 2f$, the original signal can be completely recoverable from the sampled signal with no loss of information. This is necessary, not only to avoid the aliasing effects of the actual signal content, but also to reduce the contribution of higher-frequency noise components to the fundamental components. In practice, the signal always contains high frequency components so that a low-pass filter is required to precede digital sampling process. In this work, the signal conditioner provides a low-pass filter with the bandwidth of 10kHz and the lowest sampling rate used is 25kS/s (the S/s abbreviation means Samples/second).

2.2.3 Multiple-channel scanning

To measure the phase difference, the applied voltage and current signals need to be sampled simultaneously. Thus two channels were employed, one for the analog voltage input and the other for current. The A/D board scans the two channels and performs A/D conversion in the manner shown in Fig 2.2.

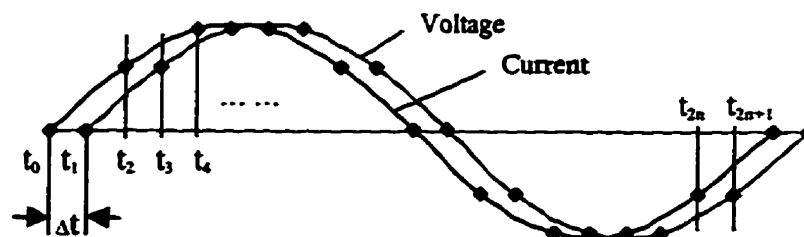


Fig 2.2: Two channel scanning

In Fig 2.2, the current signal is sampled first at time t_0 by channel-0. The voltage signal is sampled next at time t_1 by channel-1 and followed by sampling of the current signal at time t_2 by channel-0 again and so on. Finally two digitized signals of the current and voltage are obtained. The samples representing the current and voltage signals will be $\{ t_0, t_2, t_4, \dots, t_{2n} \}$ and $\{ t_1, t_3, t_5, \dots, t_{2n+1} \}$ respectively.

As may be seen from Fig 2.2, the first sample of the voltage signal is not acquired at the same time as first sample of the current signal. Therefore a time delay Δt ($\Delta t = t_n - t_{n-1}$) is introduced in the voltage signal due to the multiplexing procedure. This time delay can be taken into account by adding a phase shift α to the voltage signal. Where

$$\alpha = \frac{\pi}{n} \quad (2.1)$$

where n = the number of samples per cycle

2.3 Discrete Fourier Transform (DFT)

2.3.1 DFT

A number of high order harmonics may exist in the acquired digital signals due to electromagnetic induction, supply voltage harmonics and other disturbances.

This will cause a large measurement error and therefore the effect of the harmonics needs to be eliminated efficiently. To measure the dissipation factor, only the fundamental component is of interest.

If only a few harmonics are to be extracted from a digital signal, the DFT is faster than the FFT. One may consider using the FFT if the intention is to obtain the spectrum of a digital signal [14]. In this work, the DFT was used to extract only the fundamental component from a digitized signal thus eliminating harmonics.

In order to extract the fundamental components of voltage and current, a complete cycle of both the voltage and current signals needs to be acquired and sampled at a certain sampling rate. The sampling rate must be an integer number of times of the signal frequency, which results in what is known as synchronous sampling. Following this, the discrete-time signal V_n (voltage) and I_n (current) are obtained and can be processed by DFT, where $0 \leq n \leq N-1$.

Generally, a real discrete-time signal X_n , defined on the finite set of integers $0 \leq n \leq N-1$, can be expressed in a discrete version of the Fourier series as

$$X_n = a_0 + \sum_{k=1}^{N-1} a_k \cos(k \frac{2\pi}{N} n) + \sum_{k=1}^{N-1} b_k \sin(k \frac{2\pi}{N} n) \quad (2.2)$$

where the coefficients a_k and b_k are given by the DFT of X_n

$$\left. \begin{aligned} a_0 &= \frac{1}{N} \sum_{n=0}^{N-1} X_n \\ a_k &= \frac{2}{N} \sum_{n=0}^{N-1} X_n \cos(k \frac{2\pi}{N} n) \\ b_k &= \frac{2}{N} \sum_{n=0}^{N-1} X_n \sin(k \frac{2\pi}{N} n) \end{aligned} \right\} \quad (2.3)$$

For convenience of signal analysis, Eq(2.2) may be written as

$$X_n = A_0 + \sum_{k=1}^{N-1} A_k \sin(k \frac{2\pi}{N} n + \theta_k) \quad (2.4)$$

where

$$\left. \begin{aligned} A_0 &= a_0 \\ A_k &= \sqrt{a_k^2 + b_k^2} \\ \theta_k &= \arctan \frac{a_k}{b_k} \end{aligned} \right\} \quad (2.5)$$

where A_k is the peak amplitude of the k^{th} harmonic, and θ_k the phase of k^{th} harmonic. Only the fundamental components, A_1 and θ_1 , are of interest.

2.3.2 Analysis of harmonic components in the voltage and current signals

Most of the tests in this work are based on the 60Hz voltage from the main supply. The applied voltage is obtained from an auto-transformer connected to the wall-outlet. It is useful to know the harmonic components contained in the source voltage and in the resulting current flowing through the test object. As described above, DFT was employed to carry out the harmonic analysis.

The supply from the wall outlet (120V) was connected to a sample capacitor of value 3000pF. The voltage across it and the current flowing through it were analyzed to examine harmonic content. The results are shown in Table 2.1 (also see Fig 2.3)

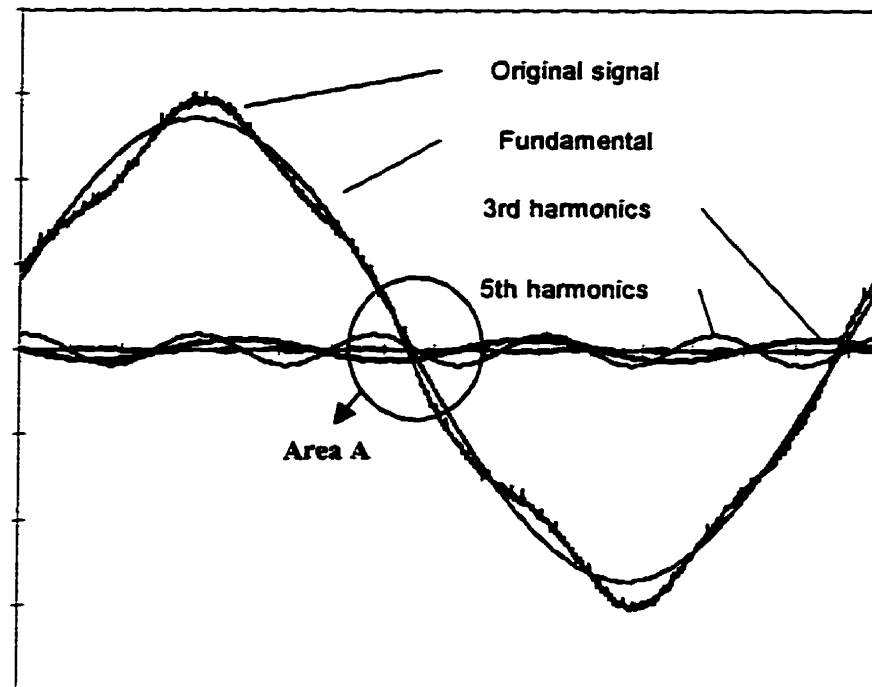
Table 2.1: Harmonics content in the applied voltage and current
(expressed in p.u. of fundamental)

	3 rd	5 th	7 th	9 th
Voltage	1.50%	1.33%	0.05%	0.08%
Current	4.66%	6.58%	0.49%	0.60%

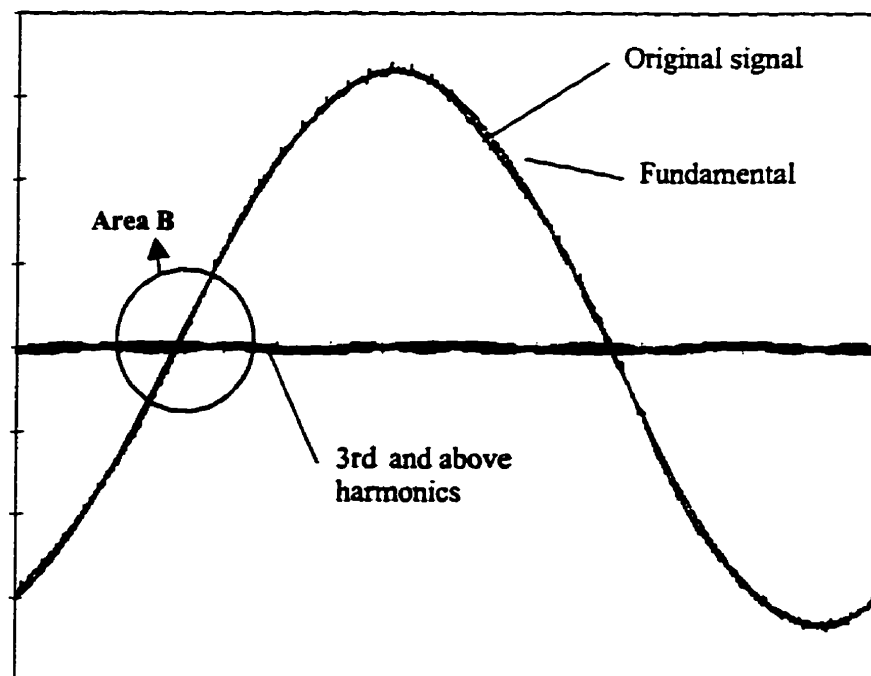
From Fig 2.3, it is seen that the harmonic content in the current signal is much more than that in the voltage signal. This is because $|I_n| = n\omega CV_n \cos(n\omega t)$, if the voltage signal is $V_n \sin(n\omega t)$ and the test object is capacitive. Where n is the order of the harmonics and C the capacitance of the test object.

Figs 2.4 (a) and (b) are close-ups of the areas labeled as A in Fig 2.3 (a) and B in Fig 2.3(b) respectively. They show how the presence of harmonics results in a shift in the zero crossing point of a contaminated signal. This can have serious effect on a digital method which relies on detecting on zero crossings.

The n^{th} voltage harmonic will cause loss in conjunction with the n^{th} current harmonic. This loss can be taken into account. However, since the magnitude of the voltage harmonics are small the accompanying loss are negligible.

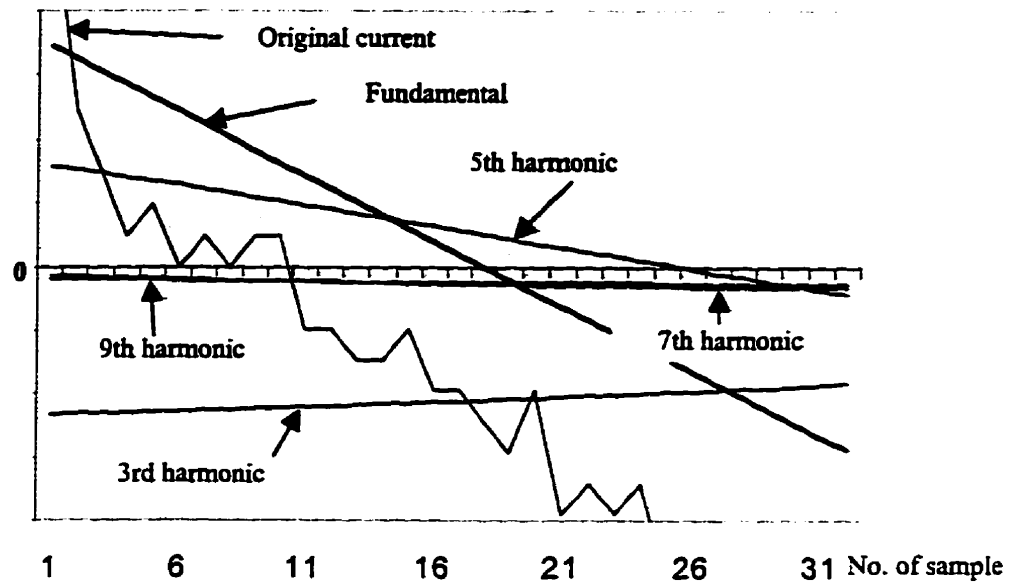


(a) Current harmonics

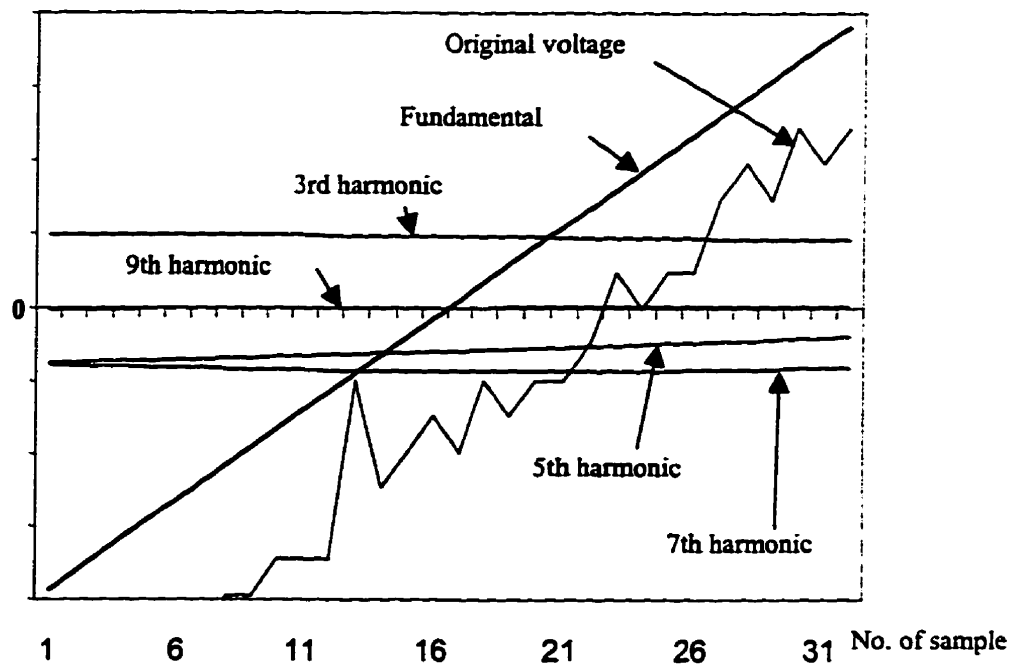


(b) Voltage harmonics

Fig 2.3: Harmonics analysis



(a) Area A: current harmonics



(b) Area B: voltage harmonics

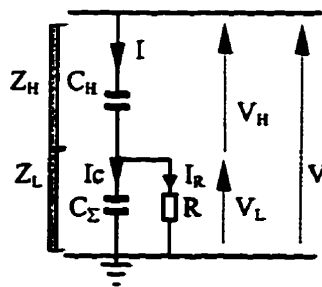
Fig 2.4: Close-up of areas labeled A and B in Fig 2.3 (a) and (b) respectively

2.4 Calibration

Measurement errors always exist due to the introduction of measurement elements such as voltage divider, shunt resistor and cables. In order to obtain accurate measurement values, these errors must be evaluated and eliminated by performing precise calibration.

2.4.1 Error due to capacitive divider

The capacitive divider causes a significant phase shift because the low voltage capacitor is shunted by the input impedance of the signal conditioner which therefore forms a R-C circuit, as shown in Fig 2.5. In Fig 2.5, C_{Σ} is an equivalent capacitance including the bottom capacitance of divider, cable capacitance and the input capacitance of signal conditioner; R is the equivalent resistance of the signal conditioner and cable.



(a)

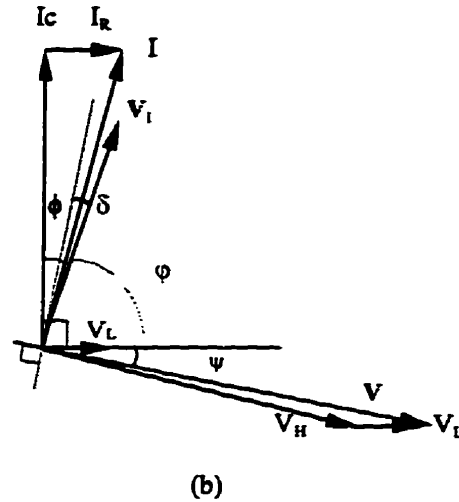


Fig 2.5: Phasor diagram of the capacitive divider system

From Fig 2.5, (2.6)

$$V_L = V Z_L / (Z_H + Z_L)$$

this gives $\psi = \tan^{-1} [1/\omega R(C_H + C_\Sigma)]$ (2.7)

because $C_H \ll C_\Sigma$, $\psi \approx \tan^{-1} (1/\omega R C_\Sigma) = \phi$ (2.8)

and $\delta = 90^\circ - (\phi + \psi)$ (2.9)

In order to find the phase shift accurately, the values of C_Σ and R must be known accurately, and should therefore be found from precise measurement.

2.4.2 Error due to shunt resistor

The shunt resistor is needed to obtain the current signal. The measurement error due to the shunt resistor can be accurately evaluated. Fig 2.6 shows the circuit and phasor diagram of the shunt resistor.

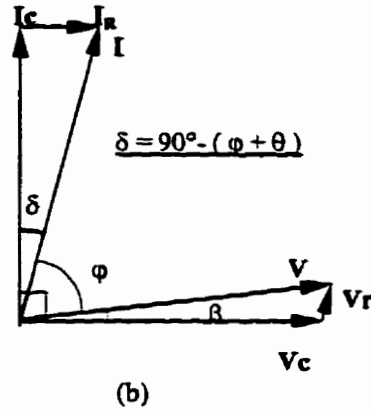
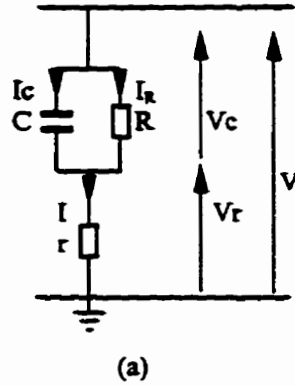


Fig 2.6: Phasor diagram of the shunt resistor system

Referring to Fig 2.6(b), I , V , V_r and ϕ may be obtained directly from the digital measurement. Using

$$V_c = V - V_r \quad (2.10)$$

or
$$V_c = \sqrt{V^2 + V_r^2 - 2VV_r \cos \phi} \quad (2.11)$$

and
$$\sin \beta = \frac{V_r}{V_c} \sin \phi \quad (2.12)$$

β can be obtained and therefore, δ may be found by

$$\delta = 90^\circ - (\phi + \beta) \quad (2.13)$$

CHAPTER 3

VALIDATION TESTS UNDER LOW VOLTAGE AND HIGH VOLTAGE

The dissipation factor measurement using the suggested digital method was carried out in the laboratory in two stages. First, low voltage measurements were carried out using a low voltage, low-loss, polystyrene capacitor. This is a basic validation step. Different sampling rates were used to study their effect on measuring errors. In the second stage, high voltage measurements were carried out using a 40kV, 500pF, resin impregnated capacitor and an artificial cavity.

3.1 Low voltage validation

3.1.1 Test set-up

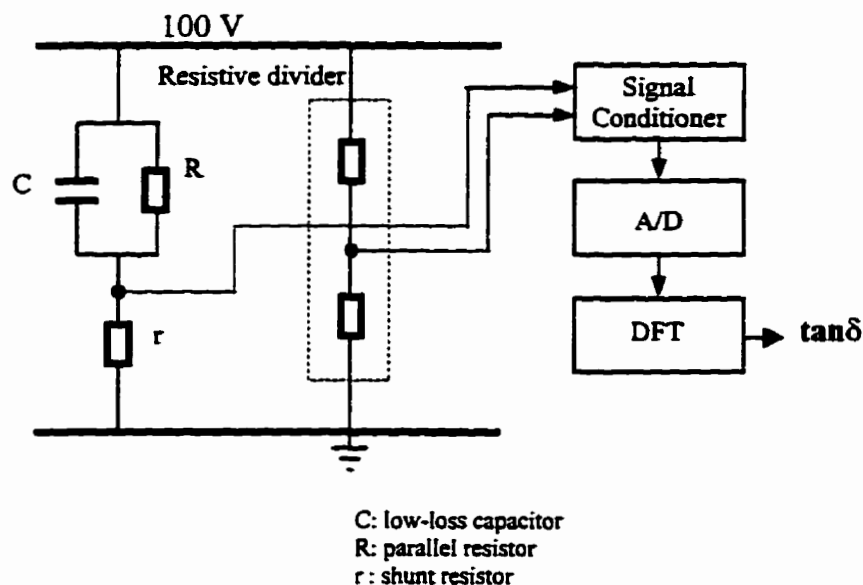


Fig 3.1: Low voltage measurement set-up

As shown in Fig 3.1, the dielectric loss was simulated by a low loss ($\tan\delta\approx 0.02\%$) 3000pF polystyrene capacitor with a carbon composition resistor in parallel. Resistors of value 100 M Ω , 160 M Ω , 270 M Ω as well as infinity (without parallel resistor) were employed to simulate different dissipation factors.

The applied voltage was 100V peak. The voltage signal was derived from a resistive divider (ratio 105:5, consisting of two wire-wound resistors, $R_H=100\text{k}\Omega$, $R_L=5\text{k}\Omega$) and the current signal obtained by measurement of the voltage drop across a 10k Ω shunt resistor (carbon composition) in the ground circuit. The resistive divider does not introduce phase shift. The measurement error due to the shunt resistor can be accurately evaluated as described in Chapter 2.

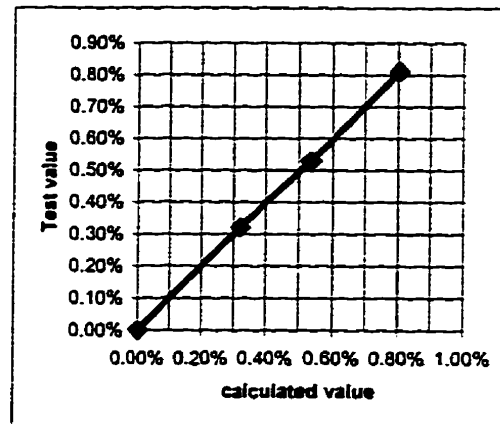
3.1.2 Test results

For each R-C combination, 100 successive measurements were taken at sampling rates of 25, 50 and 100kS/s respectively. The maximum, minimum and average values of the 100 dissipation factors measured in each case were examined. Also, the dissipation factor was calculated for each case in order to make a comparison with that obtained from the test. Table 3.1 shows the comparison of the test and calculated values at different sampling rates. In the calculation, the capacitor was assumed to be lossless. The test values listed in table 3.1 are the average values of 100 measurements.

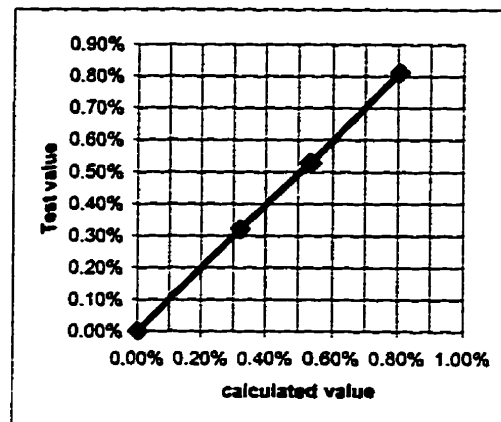
Table 3.1: Comparison of test and calculated values of $\tan\delta$

C PF	R M Ω	Calculation $\tan\delta(\%)$	Test $\tan\delta(\%)$		
			25kS/s	50kS/s	100kS/s
3056.5	∞	0.0000	0.0006	0.0046	0.0047
3056.5	270	0.3214	0.3207	0.3240	0.3296
3056.5	162	0.5357	0.5291	0.5415	0.5361
3056.5	108	0.8036	0.8109	0.8076	0.8141

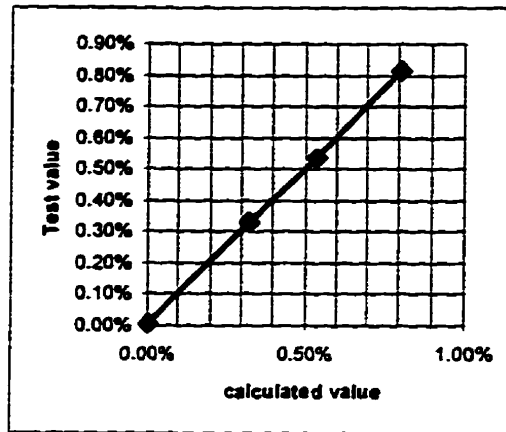
Fig 3.2 shows the comparison results in graphical form.



(a) Sampling rate: 25kS/s



(b) Sampling rate: 50kS/s



(c) Sampling rate: 100kS/s

Fig 3.2: Comparison of test values and calculated values of $\tan\delta$ at different sampling rates

3.1.3 Measurement precision at different sampling rates

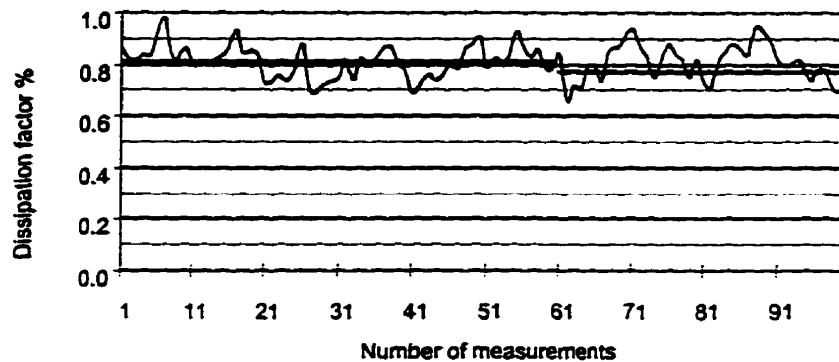
It is mentioned that the dissipation factors shown above are the average values of 100 successive measurements at each sampling rate. As in any measurement, two readings are seldom identical and the computed values display a statistical characteristic. Table 3.2 shows the measurement precision in terms of range at different sampling rates.

Table 3.2: Measurement precision at different sampling rates

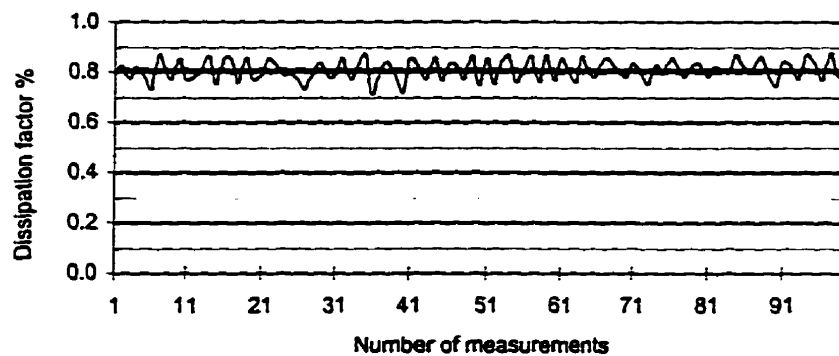
C pF	R M Ω	Measurement precision (range)		
		25kS/s	50kS/s	100kS/s
3056.5	10000000	$\pm 0.18\%$	$\pm 0.11\%$	$\pm 0.09\%$
3056.5	270	$\pm 0.18\%$	$\pm 0.10\%$	$\pm 0.10\%$
3056.5	162	$\pm 0.17\%$	$\pm 0.11\%$	$\pm 0.10\%$
3056.5	108	$\pm 0.18\%$	$\pm 0.11\%$	$\pm 0.09\%$

It is seen that the measurement error is limited to $\pm 0.10\%$ at a sampling rate of

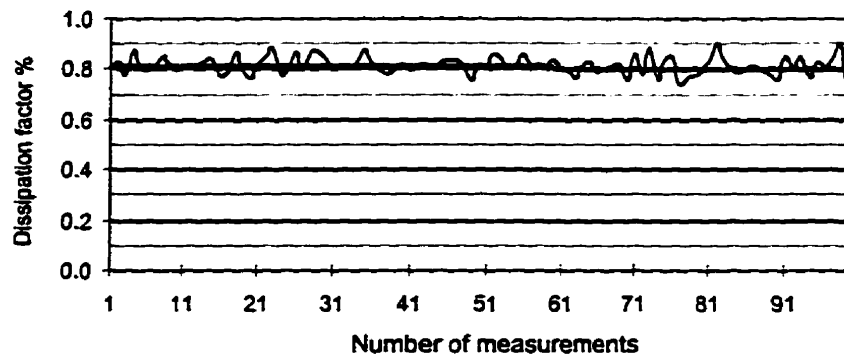
100kS/s. When the sampling rate is about 25kS/s, the error is limited to $\pm 0.18\%$. There is not much difference in the measurement error at sampling rates of 50kS/s and 100kS/s. Fig 3.3 shows the results of 100 successive measurements obtained at each sampling rate with $R=108M\Omega$.



(a) Sampling rate 25kS/s

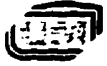


(b) Sampling rate 50kS/s



(c) Sampling rate 100kS/s

Fig 3.3: 100 successive measurement results for $R=108M\Omega$ at each sampling rate



It is also useful to assess the measurement precision in statistical terms. The probability distribution of measured dissipation factor values is assumed to be Gaussian[17]. The probability density function of the Gaussian distribution is given by

$$y = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} \quad (3.1)$$

where the standard deviation σ , is given by

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (3.2)$$

$x \in \{x_1, x_2, \dots x_i, \dots x_n\}$: random variables (measured values)

$\bar{x}$: mean value

If a set of measurements is normally distributed (see Figure 3.4), the interval

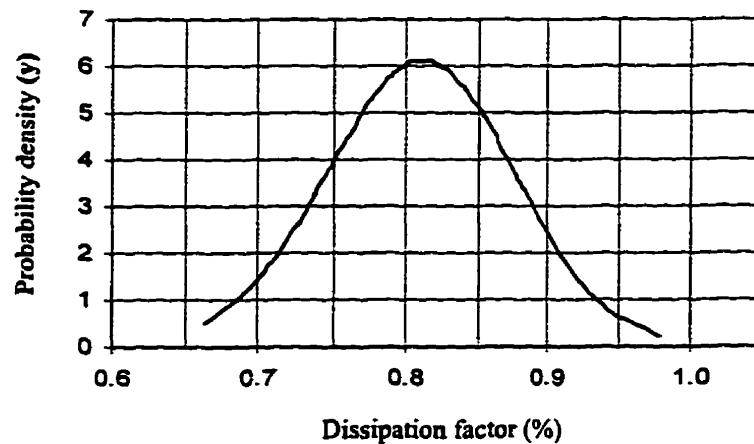
1. $\bar{x} \pm \sigma$ will contain approximately 68% of the measurements;
2. $\bar{x} \pm 2\sigma$ will contain approximately 95% of the measurements;
3. $\bar{x} \pm 3\sigma$ will contain all or almost all of the measurements.

The standard deviations of the measurements at sampling rates of 25, 50 and

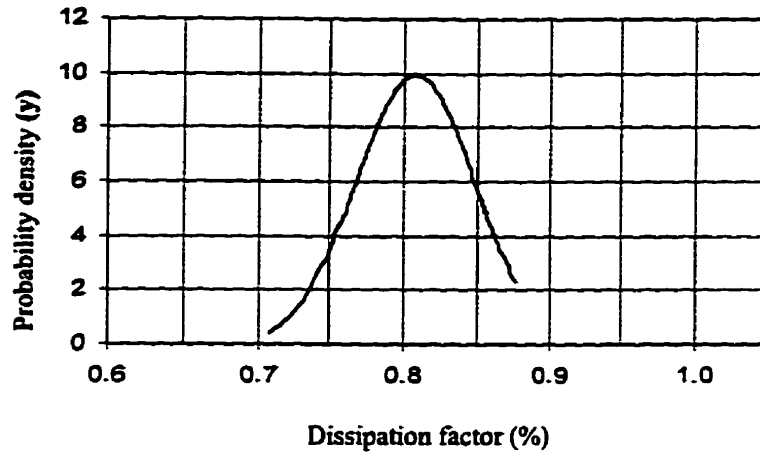
100kS/s are calculated by using Eq(3.2) and shown in Table 3.3. Also, the normal distribution curves for these three cases are calculated by Eq(3.1) and shown in Fig 3.4.

Table 3.3: Standard deviations of 100 successive measurements of dissipation factor

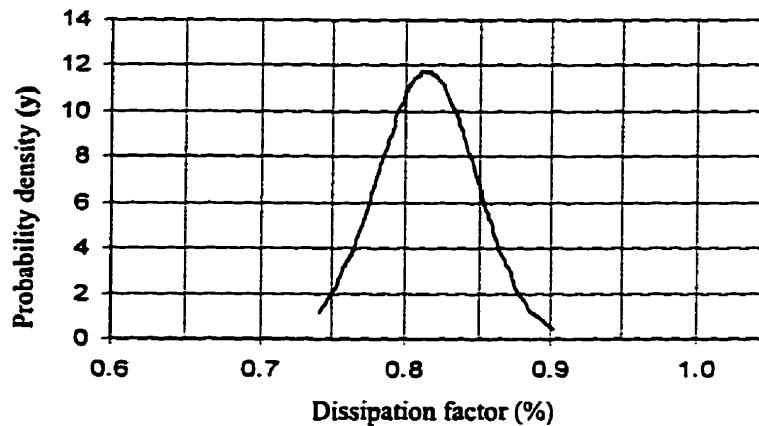
	Sampling rate		
	25kS/s	50kS/s	100kS/s
Mean value of $\tan\delta$ in %	0.8109	0.8076	0.8141
Standard deviation (σ)	0.0652	0.0401	0.0339
Interval covering 68% of all measurements	0.7457~0.8761	0.7675~0.8477	0.7802~0.8480
Interval covering 95% of all measurements	0.6805~0.9413	0.7274~0.8878	0.7463~0.8819



(a) Sampling rate 25kS/s



(b) Sampling rate 50kS/s



(c) Sampling rate 100kS/s

Fig 3.4: Normal distribution curves of the measurement values

3.1.4 Errors due to asynchronous sampling

The variation in $\tan\delta$ measurements described in the last section arise partly due to asynchronous sampling. With synchronized sampling the sampling frequency is an integer multiple (>2) of the system frequency and the fundamental and harmonic components can be correctly extracted from the input signals using DFT without resulting in “spectral leakage”.

In practice, because of the limitation imposed by the data acquisition facilities,

synchronization is impossible. With a 60Hz signal, if the chosen number of samples is 417, the sampling rate should be set to 25.02kS/s. However this rate can not be obtained because of the 1 μ s time base of the A/D board.

For example, should a rate of 25.02kS/s be specified for each channel which implies a sample interval of 19.984 μ s, the A/D board selects the nearest integer as a sample interval, i.e. 20 μ s, which corresponds to 25kS/s for each channel. In this case, there will not be an integral number of samples in one cycle thus resulting in asynchronization. With increase in sampling rate, the error due to asynchronization decreases.

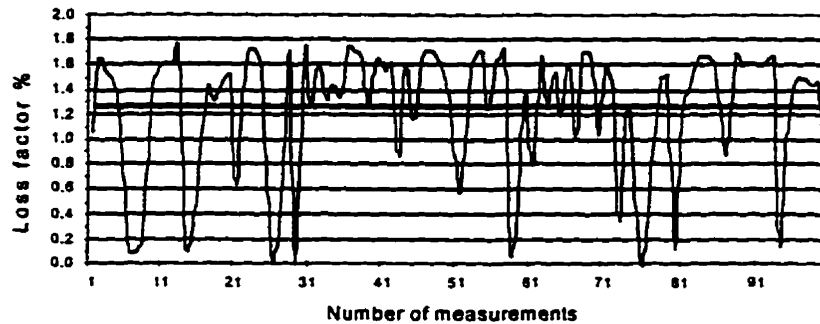
3.1.5 Further consideration about the sampling rate

As described above, two conditions need to be satisfied when choosing a sampling rate. The first condition is that the ratio of the sampling rate to the nominal system frequency must be an integer. This condition is required in order to implement the DFT. The second condition is that the sampling interval must be an integral number of the timebase of the A/D converter. In practice, it is impossible to satisfy these two conditions simultaneously if the nominal system frequency is 60Hz.

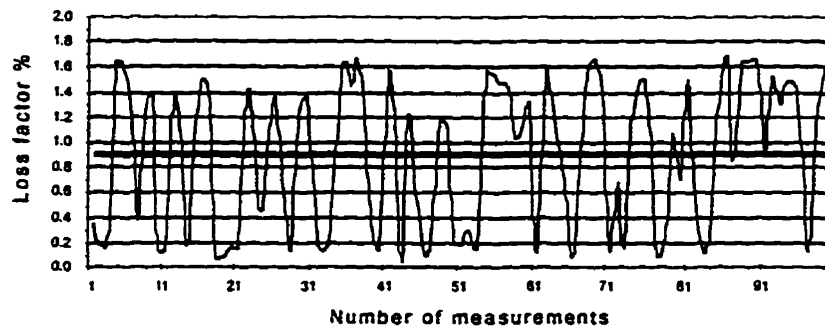
Tests were carried out to find out which of the above two conditions is more restrictive in so far as errors are concerned.

Sampling rates of 36, 60 and 90kS/s for each channel were chosen. These sampling rates are 600, 1000 and 1500 times the system frequency which resulting in sampling intervals of 13.889, 8.333 and 5.556 μ s respectively. Since the A/D converter timebase is 1 μ s, the sampling intervals are rounded off to 14, 8 and 6 μ s

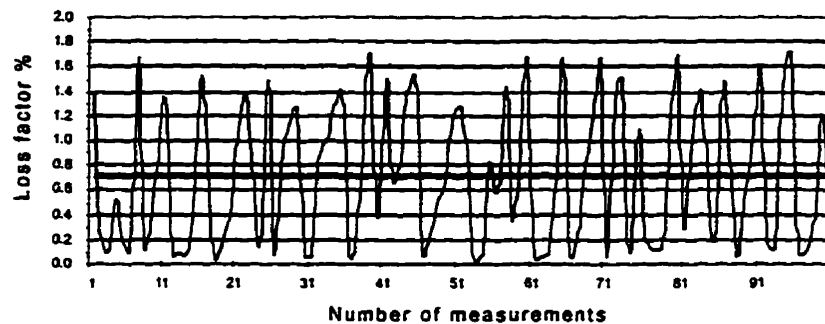
respectively by the A/D converter. These modified intervals correspond to actual sampling rates of 35.714, 58.823 and 90.909kS/s respectively. Errors are therefore introduced due to the above round procedure (see Fig 3.5).



(a) Chosen sampling rate = 36kS/s, i.e. 600 times system frequency (60Hz)



(b) Chosen sampling rate = 60kS/s, i.e. 1000 times system frequency (60Hz)



(a) Chosen sampling rate = 90kS/s, i.e. 1500 times system frequency (60Hz)

Fig 3.5: Measurement results for $R=108M\Omega$ when sampling rates are chosen to be 36, 60 and 90kS/s



These results are compared with those in Fig 3.3. The results shown in Fig 3.3 were obtained with sampling rates chosen to be 25, 50 and 100kS/s which correspond to sampling intervals of 20, 10 and 5 μ s. Obviously condition 1 is not satisfied while condition 2 is met.

Comparison of the results in Fig 3.3 and 3.5 shows that violating condition 2 causes more serious error. Table 3.4 summarizes the results.

Table 3.4: Comparison of two conditions

Condition	I			II		
Sampling rate (kS/s)	36	60	90	25	50	100
Required						
No. of Samples in a cycle	600	1000	1500	416.7	833.3	1666.7
Time interval (μ s)	13.89	8.33	5.56	20	10	5
In practice						
No. of Samples in a cycle	600	1000	1500	417	833	1667
Time interval (μ s)	14	8	6	20	10	5
Introduced errors	Large			Small		

Therefore, in the tests conducted with high voltage (see section 3.2), the sampling rates were chosen to be 25, 50 and 100kS/s. Also the current waveform was always sampled first, followed by the next sample on the voltage waveform and so on. The location of the first sample (on the current waveform) was random. Sampling was done for one cycle.

3.2 High voltage validation

3.2.1 Test set-up

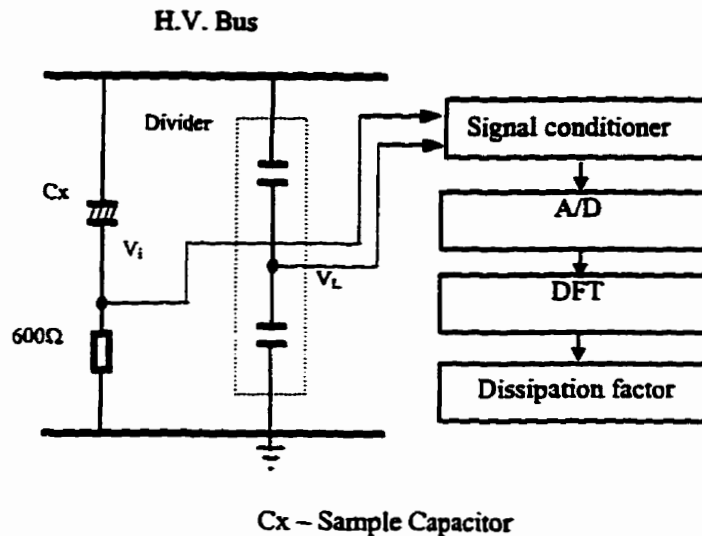


Fig 3.6: High voltage measurement setup

In the high voltage test, the applied voltage range is from 1kV to 40kV peak. To measure the dissipation factor, the voltage signal is derived from a capacitive divider and the current signal obtained by measurement of the voltage drop across a 600Ω shunt resistor in the ground circuit, as shown in Fig 3.6.

In the above set-up the measurement error due to the shunt resistor is negligible as the resistance is much less than the impedance of the sample. However, the capacitive divider causes a significant phase shift because the low voltage capacitor and the input impedance of the signal conditioning form a R-C circuit as has been discussed in Chapter 2.

The dissipation factor measurement using the suggested digital method was carried out using two different samples: an artificial cavity and a 40kV, 500pF, resin impregnated capacitor.

3.2.2 Validation with an artificial cavity

In order to validate the suggested method it was applied to measure the dissipation factor associated with partial discharge occurring in an artificial cavity (see Fig 3.7). The sampling rate was 100kS/s and the applied voltage was varied from 2~20kV peak. Loss measurements were also carried out using a current comparator. Table 3.5 compares the results obtained at several values of applied voltage.

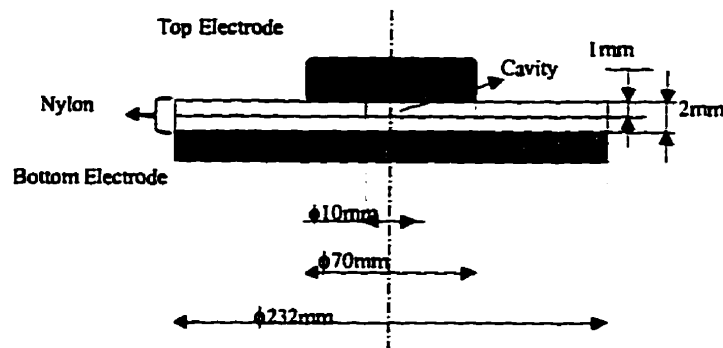
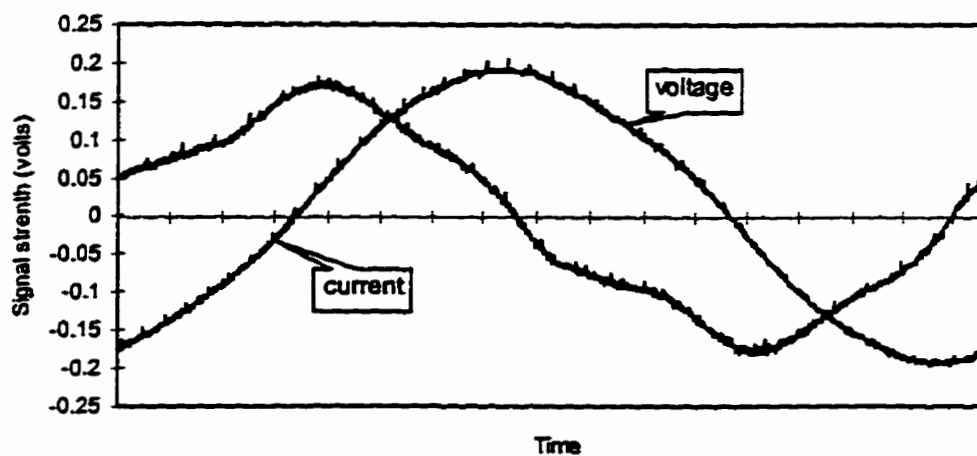


Fig 3.7: Artificial cavity

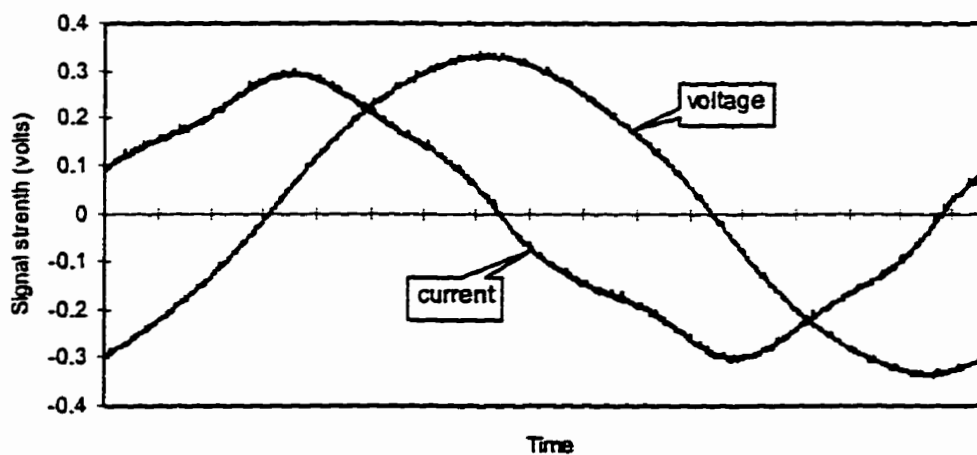
With increasing voltage, discharge activity in the void as well as the loss increase significantly. Table 3.5 shows that the dissipation factors measured using the suggested digital method are in good agreement with that using a conventional method; Fig 3.8 shows the waveforms of voltage and current obtained in the test as recorded by the A/D board.

Table 3.5: Comparison of results obtained by digital and conventional methods

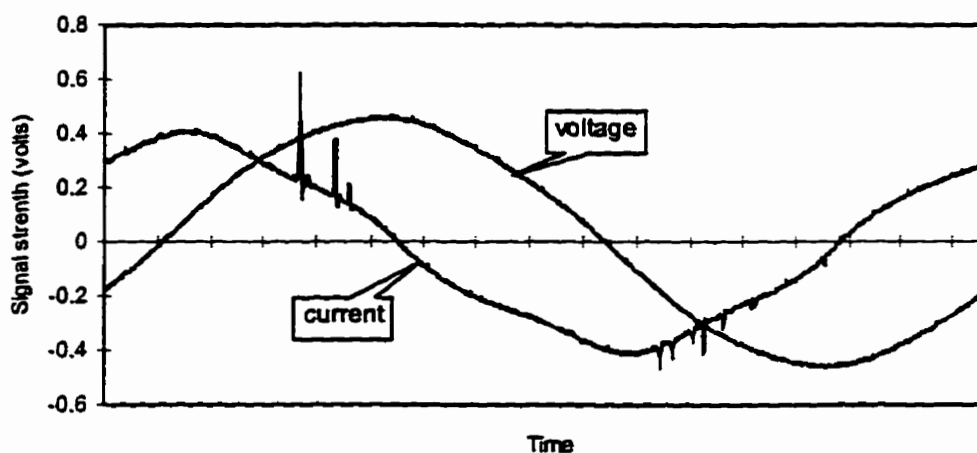
Digital method		Current comparator	
Voltage (kV, peak)	Dissipation factor (%)	Voltage (kV, peak)	Dissipation factor (%)
2.08	0.090	2.0	0.075
3.63	0.095	4.0	0.075
5.01	0.298	5.0	0.275
5.38	2.444	6.0	2.800
6.16	4.454	—	—
8.65	9.382	9.0	10.270
13.98	17.093	14.0	17.610



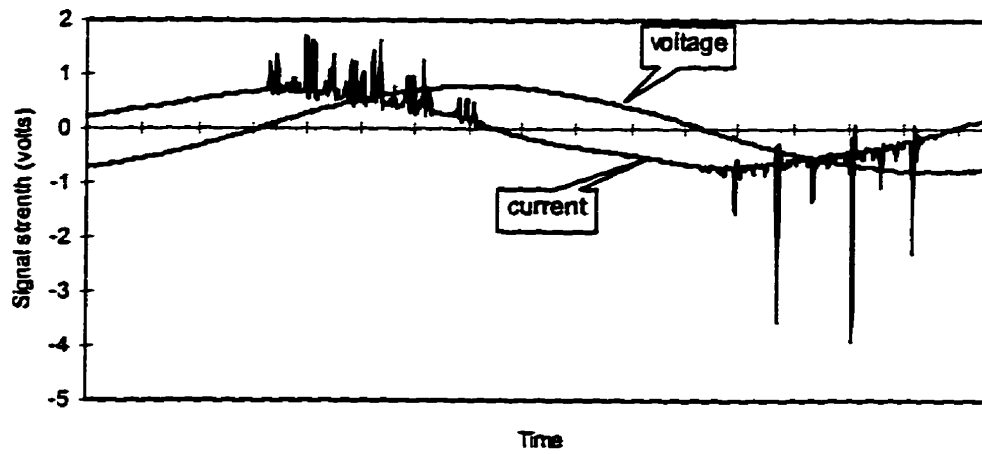
(a) Applied voltage = 2.08kV peak



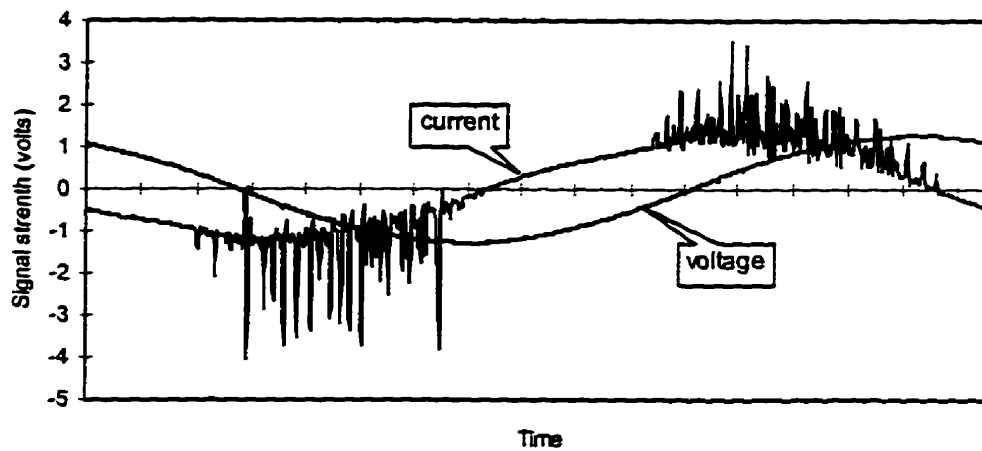
(b) Applied voltage = 4.51kV peak



(c) Applied voltage = 5.01kV peak



(d) Applied voltage = 8.65kV peak



(e) Applied voltage = 13.98kV peak

Fig 3.8: Waveforms of current and voltage at various applied voltage levels

3.2.3 Test with a sample capacitor at different sampling rate

To find the relationship between the measurement accuracy and the sampling rate in the high voltage tests, 100 measurements were carried out for a resin impregnated capacitor with sampling rates of 25, 50 and 100kS/s. The applied voltage was 40kV peak. Fig 3.9 shows the variation of dissipation factor over 100 successive measurements in each case.

As in the low voltage test, it is seen that the measured values of dissipation factor become more stable with increase in sampling rate. The error is less than $\pm 0.1\%$, $\pm 0.07\%$ and $\pm 0.05\%$ for sampling rates of 25, 50 and 100kS/s respectively. Comparing with the low voltage test results, the precision is much higher in the high voltage test. The reason is because the current signal is stronger in the high voltage test than in the low voltage test.

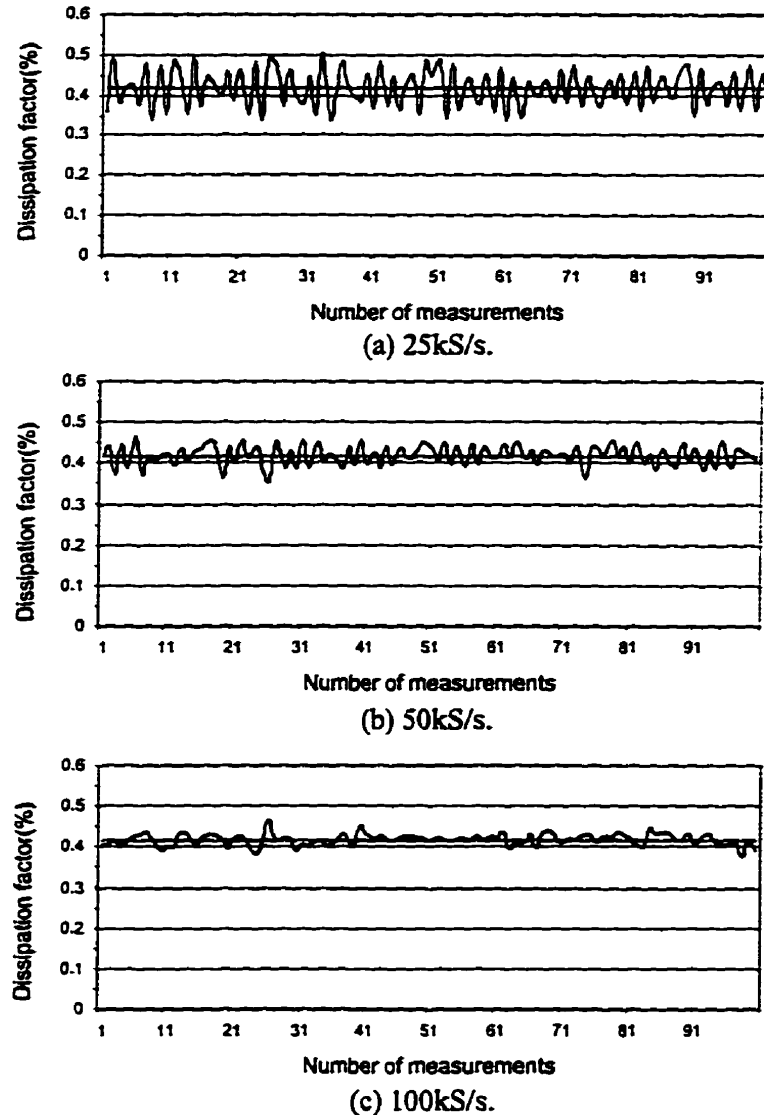
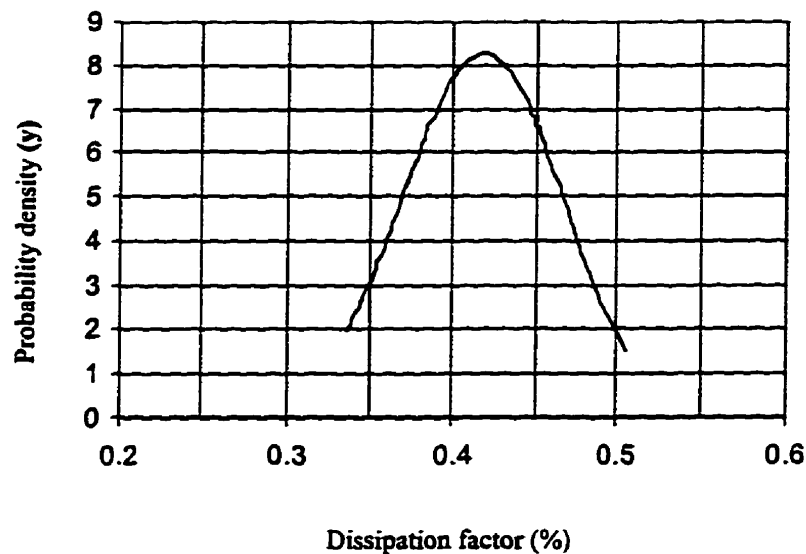


Fig 3.9: Variation of dissipation factor over 100 successive measurements

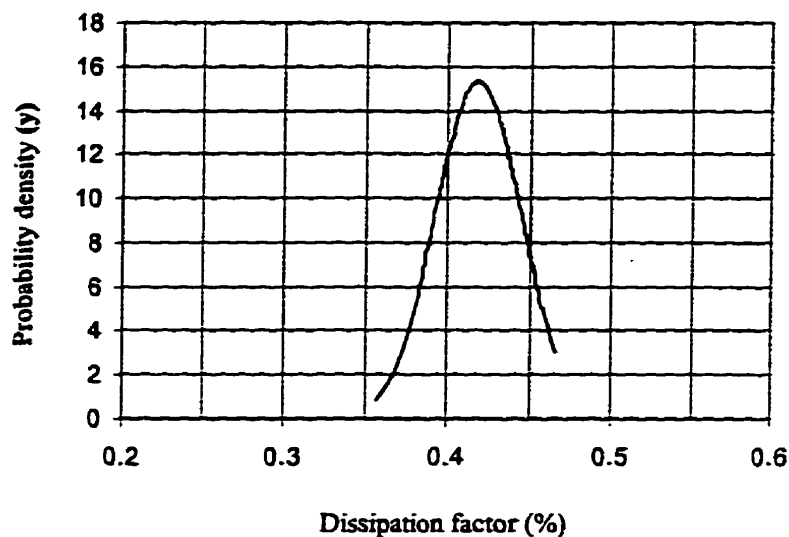
Table 3.6 shows the standard deviations of the measurements obtained in the high voltage tests at sampling rates of 25, 50 and 100kS/s. The normal distribution curves for the three cases are shown in Fig 3.10.

Table 3.6: Standard deviations of 100 successive measurements of dissipation factor in the high voltage tests

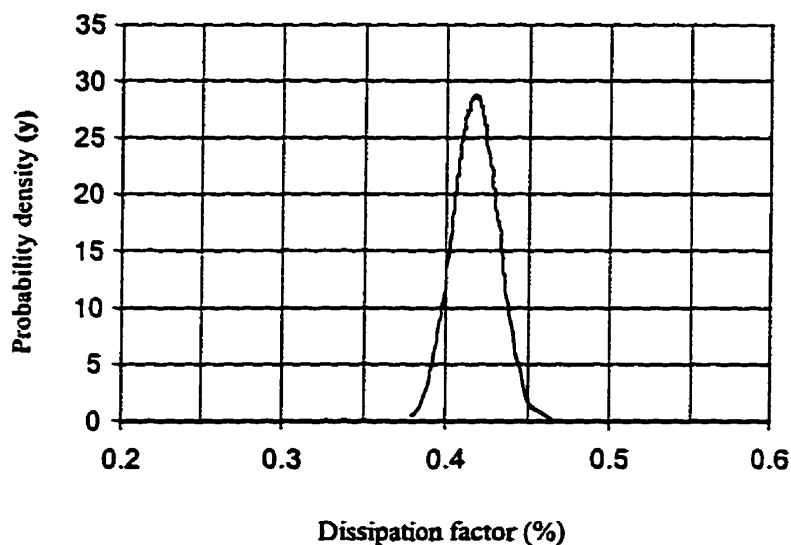
	Sampling rate		
	25kS/s	50kS/s	100kS/s
Mean value of $\tan\delta$ in %	0.4177	0.4187	0.4182
Standard deviation (σ)	0.0482	0.0260	0.0139
Interval covering 68% of all measurements	0.3695~0.4659	0.3927~0.4447	0.4043~0.4321
Interval covering 95% of all measurements	0.3213~0.5141	0.3667~0.4707	0.3904~0.4460



(a) Sampling rate 25kS/s



(b) Sampling rate 50kS/s



(c) Sampling rate 100kS/s

Fig 3.10: Normal distribution curves of high voltage measurements

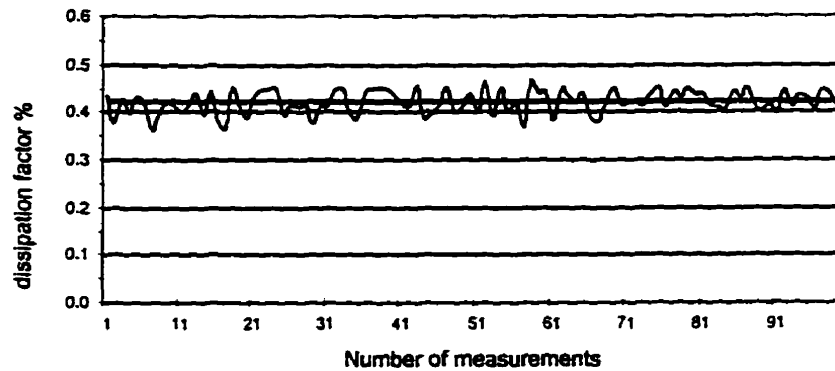
3.2.4 Tests at different voltage levels

Voltages of 10, 20 and 40kV were applied to a resin impregnated capacitor to measure its dissipation factor at a sampling rate of 100kS/s. Dissipation factor

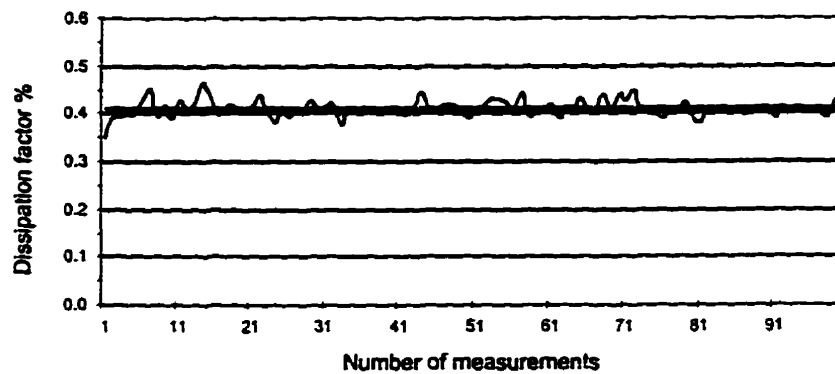
measurements were also carried out using a current comparator at the same voltages for comparison. Table 3.7 compares the measurement results obtained. Fig 3.11 shows 100 successive measurements curves at different applied voltages using the suggested digital method.

Table 3.7: Dissipation factor (%) measurement results at different voltages

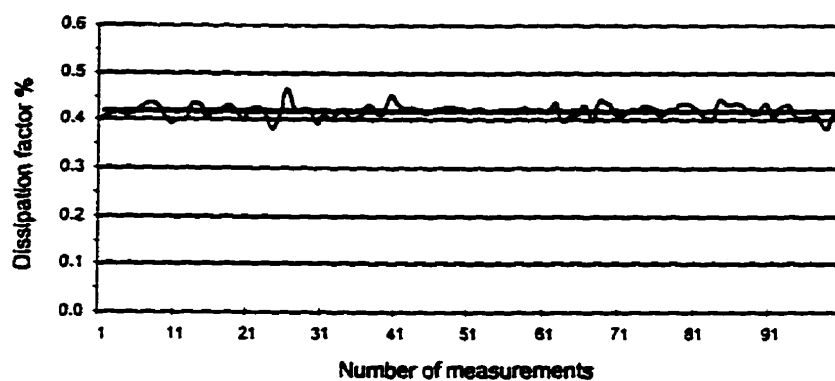
Voltage(kV, peak)	10	20	40
Suggested method	0.4210	0.4105	0.4182
Current comparator	0.41	0.41	0.42



(a) Applied voltage: 10kV peak



(b) Applied voltage: 20kV peak



(c) Applied voltage: 40kV peak

Fig 3.11: 100 successive measurements at different applied voltages



CHAPTER 4

EVALUATION AND SOLUTION OF MEASUREMENT ERRORS DUE TO SYSTEM FREQUENCY FLUCTUATION

Another factor that may contribute to measurement error is the fluctuation of system frequency. This chapter evaluates the error and presents a solution method.

4.1 Evaluation of measurement errors due to system frequency fluctuation

To extract the fundamental components using DFT, as discussed above, it is required that the number of samples within one cycle of the fundamental is an integer (synchronized sampling). Otherwise spectrum leakage is introduced which will result in measurement error. Synchronized sampling is achieved only if the sampling rate is an integral number of times of the system frequency. Once the sampling rate is chosen, the actual sampling rate will be fixed and can not be changed due to the limitation of the $1\mu\text{s}$ time base. An error will be introduced when the system frequency fluctuates because the frequency fluctuation results in asynchronized sampling.

Usually the fluctuation in the frequency of a power system is of the order of $\pm 0.05\text{Hz}$. By means of a numerical simulation, it is shown that a small and negligible error is introduced in the calculation of dissipation factor due to small frequency fluctuations.

Several pairs of sinusoid waveforms were digitally generated. Each pair has a different frequency in the range 58 ~ 62Hz but with the same phase difference ϕ . The two waveforms, comprising a pair, may be regarded as voltage and current signals. All the waveforms were sampled at a sampling rate of 249.96kS/s, which is possible in the numerical simulation method but not in practise because of the limitation imposed by the A/D board. The first sample was always taken at a fixed point on one of the waveforms comprising the pair. Next, DFT was performed and the dissipation factor was obtained for each pair of waveforms.

The phase difference ϕ between two waveforms was chosen to be 89.53° , the corresponding $\tan\delta$ is easily calculated to be 0.8203%. It is seen from Table 4.1 that the digitally calculated value of dissipation factor for this pair of waveforms with a frequency of 60Hz is exactly 0.8203%. For the pairs with frequencies of 59.95 and 60.05Hz, the digitally calculated dissipation factors are 0.8216% and 0.8200% respectively which are very close to the 60Hz value of 0.8203%; the small error is negligible.

For the pairs with larger frequency variation, the dissipation factor obtained from the digital simulation were much larger than the 60Hz value.

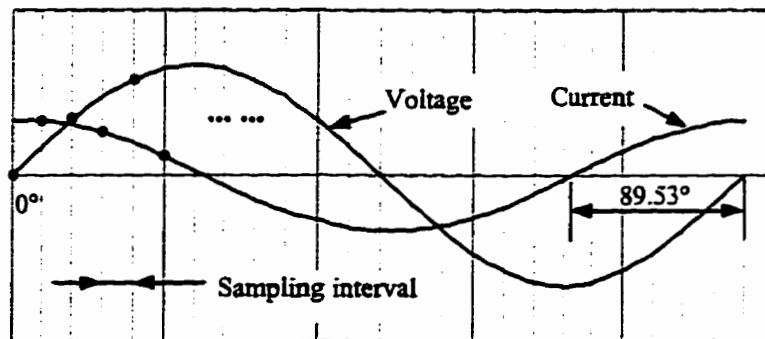
Table 4.1: Variation of calculated dissipation factor at different frequencies

Frequency (Hz)	58.00	59.00	59.50	59.95	60.00	60.05	60.10	60.50	61.00	62.00
Dissipation factor (%)	1.5578	1.0123	0.8723	0.8216	0.8203	0.8200	0.8205	0.8557	0.9772	1.4713

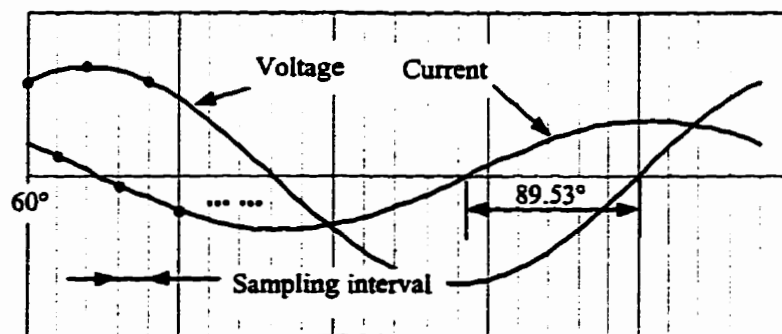
In the above simulation method, sampling was commenced at the zero degree of the voltage waveform (lagging). The following results show the effect of variation in the location of commencement of sampling.

In successive simulations, sampling was commenced on the voltage waveforms at either zero degree or at 11 other points each separated from the other by 30° . This was carried out for frequencies in the range 58 ~ 62Hz.

Fig 4.1 shows conditions for triggering at 0° and 60° on the voltage waveform. The results are summarized in Table 4.2. Fig 4.2 expresses the results of Table 4.2 in graphical form.



(a) Triggering at 0° on the voltage waveforms



(b) Triggering at 60° on the voltage waveforms

Fig 4.1: Triggering at different points on the voltage waveform

Table 4.2: Effect of frequency and triggering point on the dissipation factor(%) measurement (Actual value = 0.8203%)

Trigger Angle	Frequency(Hz)								
	58	59	59.5	59.95	60	60.05	60.5	61	62
0	1.5578	1.0123	0.8723	0.8216	0.8203	0.8200	0.8557	0.9772	1.4713
30	-1.6771	-0.5298	0.1230	0.7488	0.8203	0.8923	1.5561	2.3240	3.9299
60	-2.4141	-0.7216	0.0711	0.7475	0.8203	0.8927	1.5207	2.1672	3.2793
90	0.0838	0.6286	0.7685	0.8191	0.8203	0.8207	0.7850	0.6637	0.1702
120	3.3187	2.1706	1.5178	0.8919	0.8203	0.7484	0.0846	-0.6831	-2.2884
150	4.0557	2.3625	1.5697	0.8931	0.8203	0.7480	0.1200	-0.5263	-1.6378
180	1.5578	1.0123	0.8723	0.8216	0.8203	0.8200	0.8557	0.9772	1.4713
210	-1.6771	-0.5298	0.1230	0.7488	0.8203	0.8923	1.5561	2.3240	3.9299
240	-2.4141	-0.7216	0.0711	0.7475	0.8203	0.8927	1.5207	2.1672	3.2793
270	0.0838	0.6286	0.7685	0.8191	0.8203	0.8207	0.7850	0.6637	0.1702
300	3.3187	2.1706	1.5178	0.8919	0.8203	0.7484	0.0846	-0.6831	-2.2884
330	4.0557	2.3625	1.5697	0.8931	0.8203	0.7480	0.1200	-0.5263	-1.6378
360	1.5578	1.0123	0.8723	0.8216	0.8203	0.8200	0.8557	0.9772	1.4713

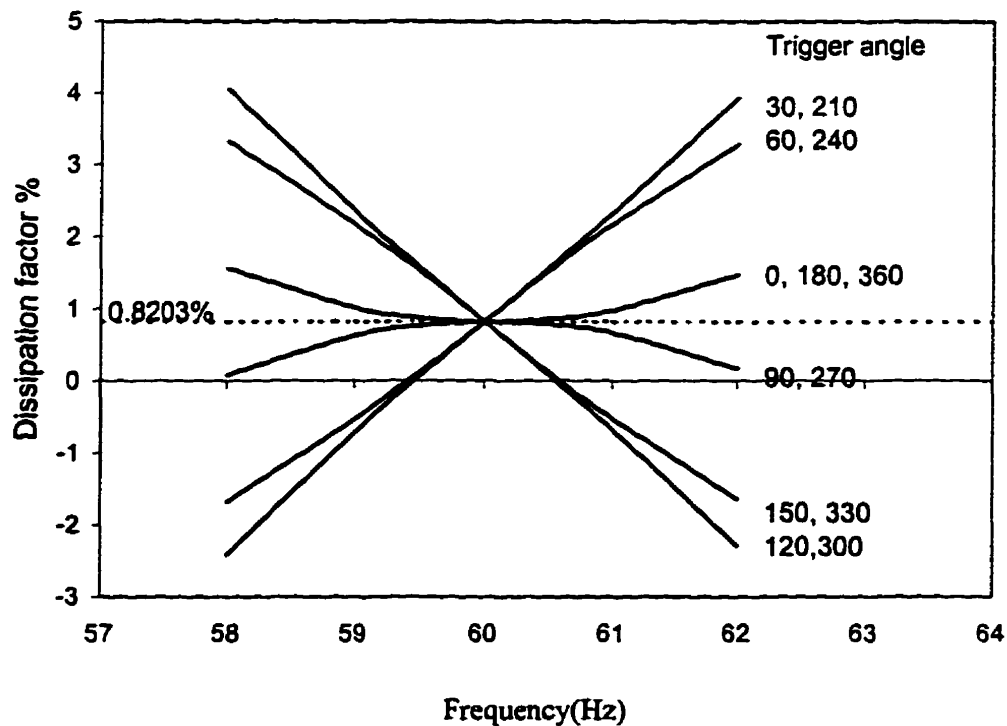


Fig 4.2: Effect of frequency and trigger point on the dissipation factor measurement

The above analysis indicates that the triggering point results in measurement error if the system frequency fluctuates widely. The error can be minimized by keeping the triggering point at or close to some specified points. In this simulation, the voltage waveform (assumed to be a sine waveform) was selected as the triggering reference waveform. It is seen from Fig 4.2 that the error is least when the triggering points are at zero crossings, positive or negative peaks of the voltage waveform.

4.2 Frequency Tracking

As demonstrated in section 4.1, the measurement error due to normal frequency fluctuation of the order of $\pm 0.05\text{Hz}$ is negligible (provided sampling is commenced at or near zero degree on a sine waveform). However, for a large system frequency variation, the error is high. In this section, a frequency tracking method is suggested to deal with frequency fluctuation.

Once the signal frequency changes, two techniques may be used to track it. The sampling rate may be adjusted while keeping the number of samples per cycle constant. A second method is to adjust the number of samples in one cycle while keeping the sampling rate constant. In practice, when the sampling rate is rather high, it can not be smoothly adjusted due to the timebase limitation. Therefore instead of changing the sampling rate directly, the number of samples per cycle was adjusted, the adjustment being dependent on the change in the frequency of the input signal.

Fig 4.3 shows the adjustment of the number of samples within a cycle. Here waveform No.2 is assumed having the system frequency; waveform No.1 has a higher

frequency and waveform No.3 has lower one. The sampling interval is maintained constant.

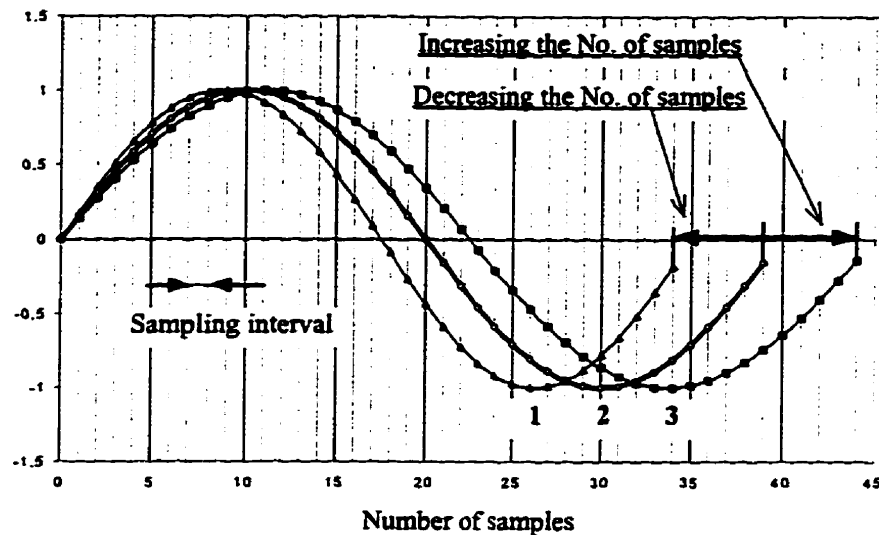


Fig 4.3: Adjustment of the number of samples within a cycle

The voltage waveform is used to detect the system frequency. The output of the DFT of a sine waveform has two components, a real and an imaginary part which forms a phasor in the X-Y plane. When the sampling window moves, the phasor rotates. Fig 4.4 shows a sine waveform sampled with 20 points/cycle and the corresponding phasors associated with three sampling windows.

Here a $\Delta\alpha/\Delta t$ method is employed to measure the system frequency.

$$f_a = (\Delta\alpha/\Delta t)/2\pi$$

where f_a – actual signal frequency

$\Delta\alpha$ – the incremental angle that the phasor rotates as the window moves “n” samples

Δt – the time used for the window to move “n” samples

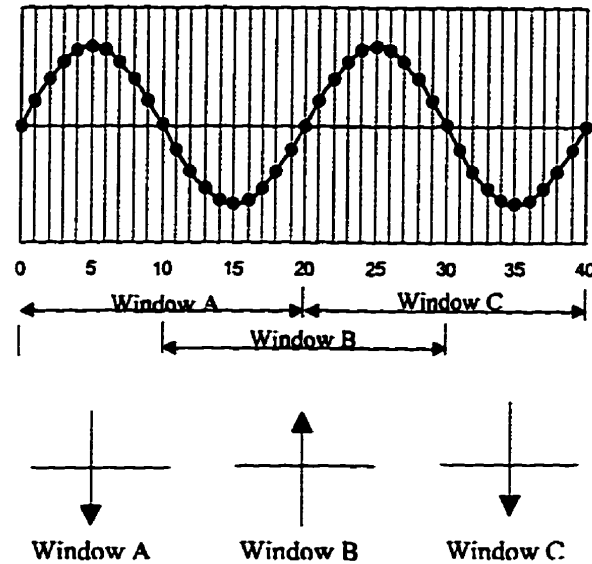


Fig 4.4: Sampling windows and phasors

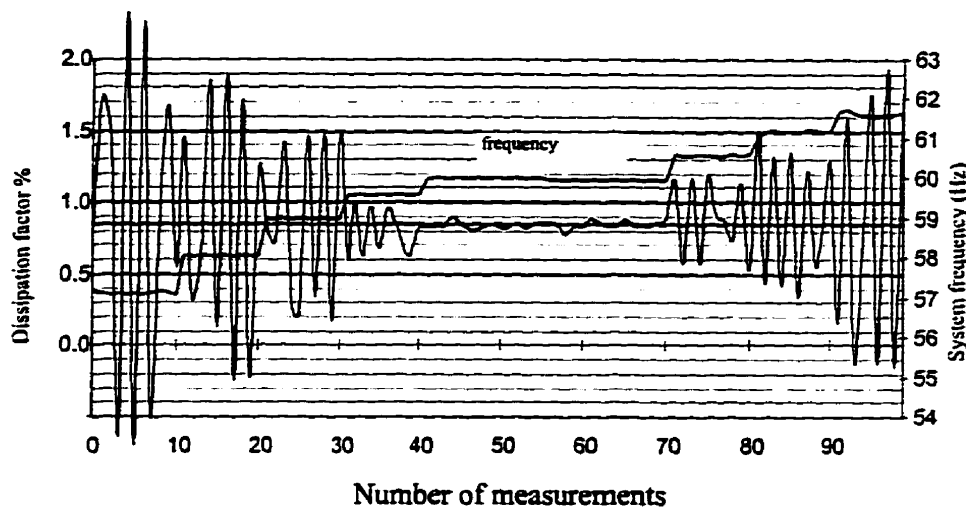
When the sampling window moves “n” samples, $\Delta t = n/f_s$; $\Delta\alpha = n \times 2\pi/N$ if the sampling frequency is exactly N times that of the signal or $\Delta\alpha = (n \times 2\pi/N) + \beta$ if it is not. The angle β is positive if the sampling frequency is less than N times that of the signal, otherwise it is negative.

In order to show the performance of the frequency tracking algorithm, 100 successive measurements were carried out with and without using frequency tracking for a frequency variation of 57.2~61.8Hz (achieved by use of a low voltage signal generator). This is a rather unusual large variation but was selected because of the limitation in the maximum sampling rate of the A/D board. Fig 4.5 shows the obvious improvement which results from implementation of the frequency tracking algorithm.

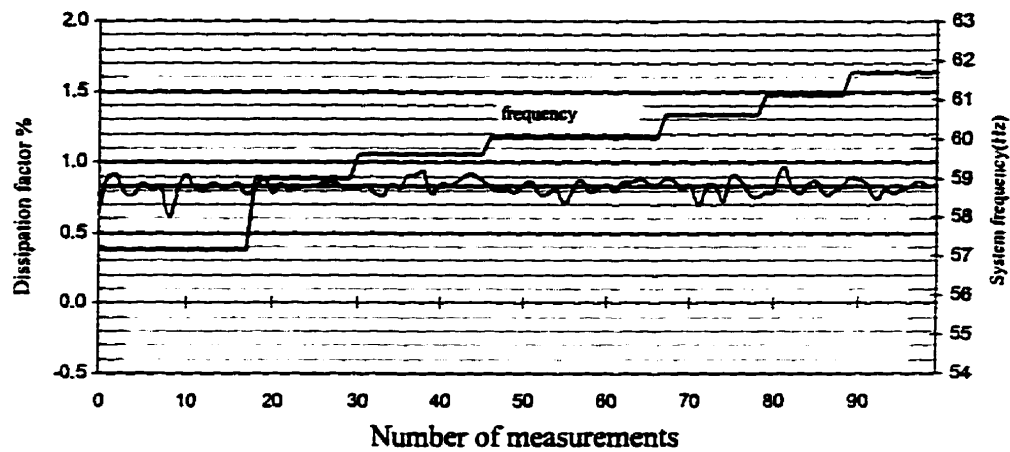
The dissipation factor was computed for the case of the low voltage capacitor with a $162\text{M}\Omega$ resistor in parallel. Fig 4.5a shows that the dissipation factor varies considerably. In this case a sampling rate of 100kS/s was employed.

The results in Fig 4.5b were obtained by using the suggested frequency tracking method. The resulting improvement is obvious.

To implement this scheme in order to accommodate frequency variation in the practical range of $\pm 0.05\text{Hz}$, a much higher sampling rate is required, i.e., of the order of 500kS/s .



(a) measurements without frequency tracking



(b) measurements with frequency tracking

Fig 4.5: Comparison of the measurement results
with and without frequency tracking

CHAPTER 5

DISSIPATION FACTOR MEASUREMENT WITH A DIGITAL OSCILLOSCOPE AS THE A/D CONVERTER

In the work described in the preceding chapters, an A/D board was used to digitize the data. In this chapter the results obtained by using a digital oscilloscope are described. This was carried out to check if the high bandwidth and sampling rate of the oscilloscope would result in a more accurate measurement.

5.1 Measurement setup

The test setup and data acquisition system using an digital oscilloscope is shown in Fig 5.1.

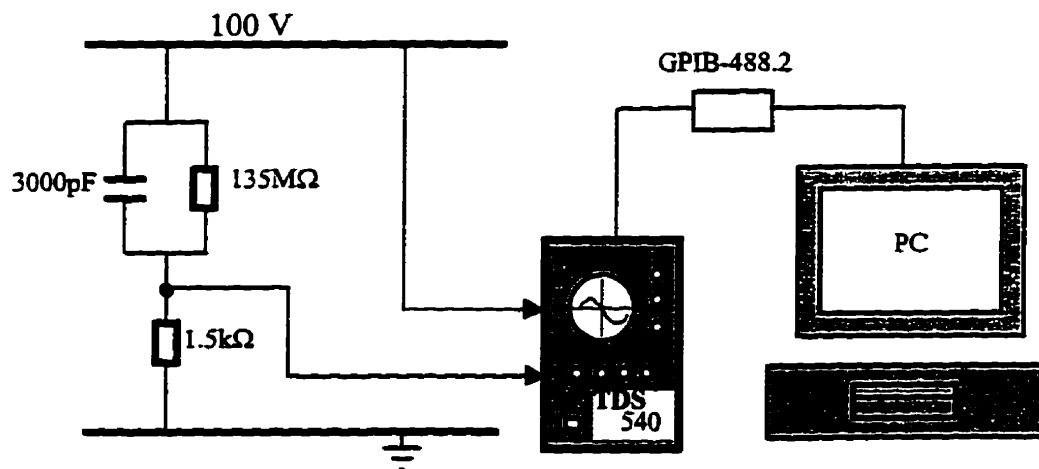


Fig 5.1: Low voltage measurement set-up using an oscilloscope

In Fig 5.1, the voltage signal was derived directly from the voltage bus and the current signal obtained by measuring the voltage drop across a shunt resistor. A

digital oscilloscope and a GPIB interface board replace the signal conditioner and A/D board used earlier. The acquired voltage and current signals were digitized by the oscilloscope, and the data in digital form was transferred to a PC through the GPIB. Finally, data acquisition software was used for the dissipation factor calculation.

5.2 TDS-540 digital oscilloscope

The Tektronics TDS-540 digital oscilloscope has a 8-bit sampling A/D converter. The maximum sampling rate is 1GSamples/sec. It also has a filter with a bandwidth of 100MHz. Use of the oscilloscope enables one to use high sampling for data acquisition but the accuracy is relative lower due to the 8-bit A/D converter. The detailed specifications of TDS-540 are listed in Appendix A. The LabWindow V2.0 software was used to support the GPIB for obtaining and transferring data and support the measurement program.

In contrast with the A/D board used earlier in this work, the TDS-540 takes samples almost simultaneously from both channels. The maximum time delay between any two channels is only 250ns, which accounts for a maximum phase shift of 0.0054° , the corresponding error in $\tan\delta$ is less than 0.01%. Therefore this time delay is negligible.

5.3 Test results

The dissipation factor obtained by calculation (corresponding to the R and C values in Fig 5.1) is 0.825%. Ten measurements were carried out by using different

sampling rates. Table 5.1 lists the computed values of dissipation factor and Fig 5.2 shows the corresponding variation.

Table 5.1: List of the dissipation factors (%) measured by using oscilloscope

No.	1	2	3	4	5	6	7	8	9	10
250kS/s	0.978	0.840	0.606	0.857	0.946	0.701	1.049	0.871	0.714	0.883
100kS/s	0.796	0.588	0.675	0.976	0.649	0.897	0.494	1.121	0.801	1.238
50kS/s	0.382	1.424	0.962	1.192	1.004	0.405	1.115	0.796	0.698	0.279
25kS/s	1.004	0.655	0.944	0.344	-0.09	1.082	1.065	1.215	1.513	0.476

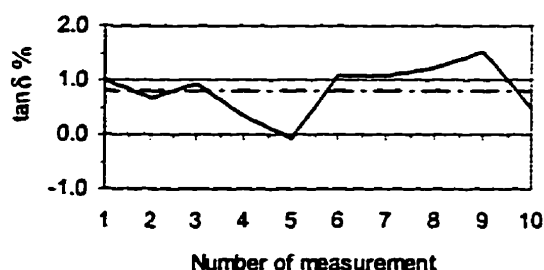
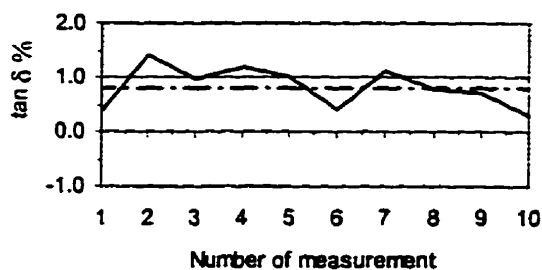
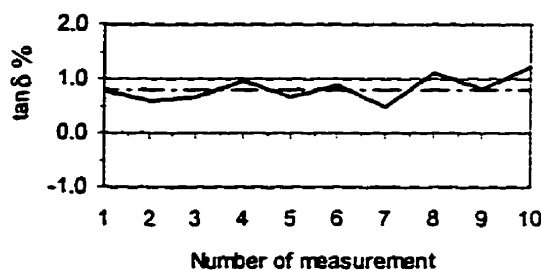
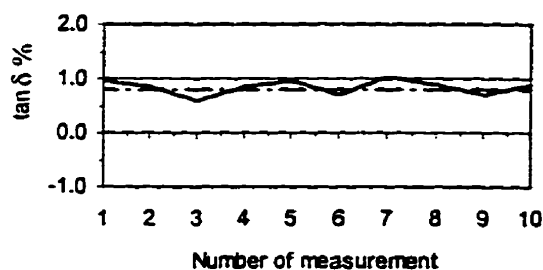
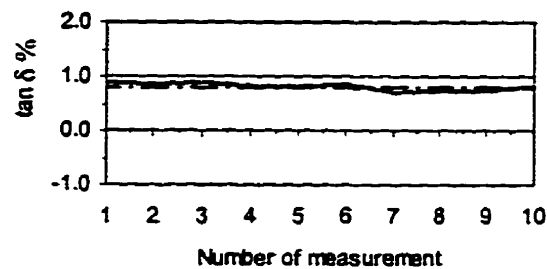


Fig 5.2: Variation of dissipation factor measured over 10 measurements
by using the TDS-540 oscilloscope

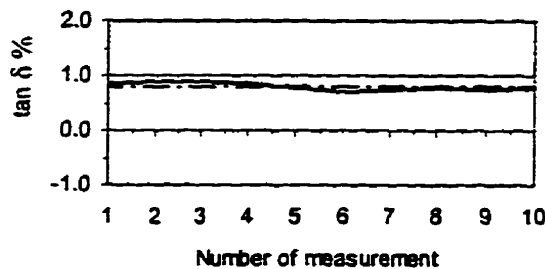
It is found that the error decreases with increase in sampling rate. The values of dissipation factor obtained by use of the oscilloscope are compared with those obtained by use of the AT-MIO-16F-5 board. The measurement results are shown in Table 5.2 and Fig 5.3.

Table 5.2: List of the dissipation factors (%) measured by using A/D board

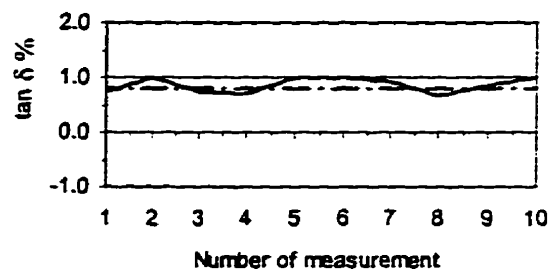
	1	2	3	4	5	6	7	8	9	10
100kS/s	0.897	0.850	0.883	0.809	0.815	0.863	0.720	0.736	0.733	0.812
50kS/s	0.842	0.885	0.898	0.837	0.792	0.712	0.737	0.784	0.758	0.790
25kS/s	0.751	1.011	0.733	0.698	0.995	1.013	0.908	0.681	0.838	1.008



(a) Sampling rate: 100kS/s



(b) Sampling rate: 50kS/s



(c) Sampling rate: 25kS/s

Fig 5.3: Variation of dissipation factor measured over 10 measurements
by using the AT-MIO-16F-5 board

Comparing the results in Figs 5.2 and 5.3, it is seen that the measurement precision using the oscilloscope is much lower than that using the A/D board. The main reason is because the sampling resolution of the oscilloscope is lower than that of the A/D board.

Table 5.3 compares the precision of results obtained through use of the

oscilloscope and the A/D board. For example, at a sampling rate of 100kS/s the variation in dissipation factor obtained with the A/D board is $\pm 0.01\%$ and with the oscilloscope is $\pm 0.40\%$. It is seen that the A/D board performs better.

**Table 5.3: Dissipation factor measurement precision by
oscilloscope and A/D board**

Device	Sampling rate (kS/s)			
	250	100	50	25
TDS-540 oscilloscope	$\pm 0.25\%$	$\pm 0.40\%$	$\pm 0.60\%$	$\pm 0.90\%$
AT-MIO-16F-5 board	—	$\pm 0.10\%$	$\pm 0.11\%$	$\pm 0.18\%$

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

A digital method has been suggested for the on-line computation of the dissipation factor of high voltage apparatus. The method is based on using the DFT to detect the phase difference between voltage and current.

Chapter 1 briefly introduces the various conventional techniques and the existing on-line methods for detecting problems in electric insulation. In Chapter 2, the measurement principle of the proposed method, the test setup and procedures are described. Calibration of the measurement system and methods employed to eliminate measurement errors are also discussed. Chapter 3 describes validation tests under low voltage and high voltage conditions. Different sampling rates of an A/D board were used to study their effect on measuring errors. The effect of the system frequency fluctuation on the measurement was evaluated and a frequency tracking method has been suggested in Chapter 4. Chapter 5 discusses the results obtained through the use of a digital oscilloscope as the A/D converter.

Based on the work completed in this research, the following conclusions may be drawn:

1. The suggested method is suitable for implementation for on-line measurement of dissipation factor of high voltage apparatus.



2. Since the method employs the DFT, instead of relying on detection of zero crossings, it can effectively eliminate errors due to harmonics. It has an additional advantage in that the error introduced due to noisy data is smaller than that present in a method which relies on detection of zero crossings.
3. The sampling rate must be chosen so that the ratio of sampling rate to timebase of the A/D converter is an integer.
4. The errors due to asynchronized sampling may be minimized by using high speed data acquisition facilities.
5. The effect of normal fluctuation of the system frequency on the measurement accuracy is negligible. For abnormal frequency fluctuation, frequency tracking can be used to improve measurement accuracy. The measurement accuracy can also be improved by keeping the triggering point at specified points.
6. The measurement accuracy of dissipation factor at a sampling rate of 100kS/s and under high voltage condition is $\pm 0.05\%$.
7. The method was validated by comparison with the results obtained by a conventional bridge measurement.
8. The time for 100 measurements with a 33MHz 386-PC at the sampling rate of 100kS/s is 98 seconds.

6.2 Suggestions for future work

The work completed in this research is only a preliminary study on the digital method of dissipation factor measurement using DFT algorithm. Suggestions for future work include:



1. The measurement precision is related to the sampling rate and sampling accuracy. Therefore more advanced A/D board with a higher sampling rate ($>500\text{kS/s}$) and sampling accuracy (resolution $\geq 16\text{bit}$) may be used to increase the measurement precision.
2. It is found by numerical simulation that the measurement accuracy depends on the triggering point at which sampling is commenced. This aspect needs further investigation.
3. All the tests in this work were carried out under laboratory conditions. It would be of great value to use this method to conduct tests on high voltage apparatus in situ.
4. The shunt resistor should be replaced by a sensitive current monitor.
5. The possibility of deriving the voltage signal from an electric field sensor should be explored.
6. To implement this method in practice, it is suggested that 20 to 30 measurements should be taken at one minute intervals and only the average value of dissipation factor displayed.



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Appendix A

Data Acquisition System Specifications

1. AT-MIO-16F-5

Sampling rate	200kS/s maximum
Timebase clock	1MHz maximum (available on board)
Base clock accuracy	$\pm 0.01\%$
Resolution	12-bit, 1 in 4096
Input range	-5 ~ +5V /10V(bipolar/unipolar)
Input impedance	100G Ω in parallel with 50pF
Gain accuracy	$\pm 0.5\%$
Input settling time	5 μ s maximum
Temperature coefficient	$\pm 4\mu$ V/ $^{\circ}$ C maximum

The AT-MIO-16F-5 is capable of single channel or multiple data acquisition at any gain without introducing settling inaccuracies. This means the AT-MIO-16F-5 performs any data acquisition operation at the maximum specified rate of 200kS/s with error-free data.

2. 5B41 input module (signal conditioner)

Input range	-10V ~ +10V
Output range	-5V ~ +5V



Accuracy	$\pm 0.05\%$
Bandwidth (-3dB)	10kHz
Input resistance	650k Ω
Input offset	$\pm 20\mu\text{V}/^\circ\text{C}$
Output offset	$\pm 40\mu\text{V}/^\circ\text{C}$
Noise	20mV, peak-peak

3. TDS-540 digitizing oscilloscope

Sampling rate	1GS/s maximum
Timebase clock	100GHz maximum
Base clock accuracy	--
Resolution	8-bit, 1 in 256
Input range	-100 ~ +100V/100V (bipolar/unipolar)
Input impedance	1M Ω in parallel with 10pF or 50 Ω
Delay between channels	<250ns
Accuracy, DC gain	$\pm 1\%$
Bandwidth	100MHz, maximum
Available to communication via GPIB-488.2 (General Purpose Interface Bus)	

Appendix B

Measurements Programs

Program 1 Dissipation factor measurement with the AT-MIO-16F-5

/*
The program is for data acquiring and dissipation factor calculation through the AT-MIO-16F-5.

Run environment: LabWindow/CVI

Analog input: channel 0 and channel 1 (-5V - +5V)

*/

```
#include <ansi_c.h>
#include <utility.h>
#include <formatio.h>
#include <dataacq.h>
#define pi 3.141592654

static double u[10000],i1[10000];
static short gain[2],ch[2];
long hdl,cyc,i,daqerr,samp;
long tsamp,samp2,kk,item,j,n,ff;
short buff[30000];
double volt[20000],rate,wt,alf,maxlf,minlf;
double rsamp,alfa,freq1,samp1,crit;
double uamp,uangle,uangle1,iamp,iangle;
double ire,iim,ure,uim,phd,losf,freq;
double vc,w,c,s,r,res,rlf,dr,rd,aa,bb,cc;
double ratio,ii,ic,ir,cl,delta,vphs;
char filename[40];
```



```
char strbuffer[20];

main()
{

    Cls();
    FmtOut("\n          *****
");
    FmtOut("\n          ***    A/D    --  Dissipation factor Program
*** ");
    FmtOut("\n          *****
");
    FmtOut("\n          Analog Input : Max:  -5v - +5v    Current signal
-- Ch0");
    FmtOut("\n                               Voltage signal
-- Ch1\n");
/* Specify the sampling rate, number of cycles, number of samples */

    FmtOut ("\nPlease Input the Sampling Rate (Ksample/sec.):");
    ScanIn ("%f",&rate);

    FmtOut ("\nPlease input the Resistance of Series Resistor(kohm):
");
    ScanIn("%f",&res);

    FmtOut ("\nFrequency Tracking or Not(1/0)? : ");
    ScanIn("%d",&ff);

    FmtOut ("\nPlease input the filename to load data: ");
    ScanIn("%s",filename);

    rate=rate*1000.; samp = rate/60;  samp1=rate/60.; /* in terms
of one channel */
    if(samp1-samp>0.555) samp = samp+1;
    tsamp = 2*samp;

    FmtOut ("\n Sample Rate = %f[p4]", rate);
```



```
    FmtOut ("\nSampling and Calculating ... Please wait ... \n");

    hdl =OpenFile(filename,2,0,1);

    FmtFile(hdl,"Date: %s\tTime: %s\n\r", DateStr (), TimeStr ());

    FmtFile(hdl,"\n No.      V          f      Sample      L.F.  Ref.ph.sh.
V-i    V-v");
    FmtFile(hdl,"\n
=====");

    FmtOut("\n No.      V          f      Sample      L.F.  Ref.ph.sh. V-i
V-v");
    FmtOut("\n
=====");

/* Following data is subject to change - once for each set-up */
if(res!=0.)
{
    ratio=(99.4+4.782)/4.782;      /* divider ratio */
    vphs = 0.;                    /* divider phase shift in angle -
absolute value*/
    res = res*1000.;
}
else
{
    ratio=11040.;
    vphs = 7.77; /*This number is subject to change with the
calibration test results */
}

/*specify the channels & gains*/
ch[0]=0;
ch[1]=1;
gain[0]=2;
gain[1]=2;
```



```
/* Aquire data, scale & store in buffers */

/* Start sampling and calculating */

n=100;
kk=0;
alf=0.;
maxlf=-10.;
minlf=10.;

while(kk<n)
{
    daqerr = AI_Clear(1);
    daqerr = DAQ_DB_StrTransfer(1, strBuffer,cyc,item);
    daqerr = DAQ_VScale (1, 0, 1, 1.0, 0.0, tsamp*2, buff,
volt);
    daqerr = SCAN_Op (1, 2, ch, gain, buff, tsamp*2, rate*2,
0.);

    for (i=0;i<tsamp;i++)
    {
        i1[i]=volt[2*i];
        u[i]=volt[2*i+1]; /*saperate data into 2 channels*/
    }

    dr = pi/180.;
    rd = 180./pi ;
    w  = 2*pi*60.;

/* To ferform DFT */

    freq=60.;
    freq1=70.;
    item=0 ;

    crit = 0.02;
    if(rate<40000.) crit=0.05;
    while(fabs(freq1-freq)>crit && item<10)
    {
        item++;
    }
}
```



```
    freq1 = freq;
    /* initialize */
    ire=0.;
    iim=0.;
    ure=0.;
    uim=0.;

    for (i=0;i<samp;i++)
    {   wt=i*2.*pi/samp;
        s = sin(wt);
        c = cos(wt);
        ure += u[i]*s;
        uim += u[i]*c;
        ire += i1[i]*s;
        iim += i1[i]*c;
    }

    uangle = atan(uim/ure);
    uamp = fabs((2./samp)*ure/cos(uangle));
    uangle = uangle*rd-360./(2.*samp);

    iangle = atan(iim/ire);
    iamp = fabs((2./samp)*ire/cos(iangle));
    iangle = iangle*rd;
    if(ure<=0.) uangle=180.+uangle;
    if(ire<=0.) iangle=180.+iangle;
    if(iangle-uangle>0.) phd = iangle-uangle;
    else phd = 360.-fabs(iangle-uangle);

    phd = phd+vphs-0.021;
    rlf = tan((90.-phd)*dr);

    /* To calculate the FREQUENCY */
    if(ff==1)
    {

        ure=0.;
        uim=0.;
```



```
j=0;

for (i=samp/2;i<samp+samp/2;i++)
{
    wt=j*2.*pi/samp;
    s = sin(wt);
    c = cos(wt);

    ure += u[i]*s;
    uim += u[i]*c;
    j++;
}
uangle1 = atan(uim/ure);
uangle1 = uangle1*rd-360./(2.*samp);
if(ure<=0.) uangle1=180.+uangle1;
if(uangle1-uangle>0.) uangle1 = uangle1-uangle;
else uangle1 = 360.-fabs(uangle1-uangle);

freq = fabs(uangle1*dr/(pi*samp/rate));

ure=0.;uim=0.; j=0;

for (i=samp/4;i<samp+samp/4;i++)
{
    wt=j*2.*pi/samp;
    s = sin(wt);
    c = cos(wt);
    ure += u[i]*s;
    uim += u[i]*c;
    j++;
}
uangle1 = atan(uim/ure);
uangle1 = uangle1*rd-360./(2.*samp);
if(ure<=0.) uangle1=180.+uangle1;

if(uangle1-uangle>0.) uangle1 = uangle1-uangle;
else uangle1 = 360.-fabs(uangle1-uangle);
```



```
freq = (fabs(2.*uangle1*dr/(pi*samp/rate))+freq)/2.;
if(item>5) freq = (freq1+freq)/2.;

w = 2.*pi*freq;
samp1 = rate/freq;
samp = rate/freq;

if(samp1-samp>0.555) samp = samp+1;

}

uamp=uamp*ratio;
}

/* to eliminate the shunt resistor's effect on dissipation factor
*/

if(res!=0.)
{
    ii = iamp/res;

    vc = sqrt(uamp*uamp+iamp*iamp-2.*uamp*iamp*cos(phd*dr));
    aa = asin(sin(phd*dr)*iamp/vc)*rd;
    delta = 90.-phd-aa;
    rlf = tan(delta*dr);
}

s = sqrt(2.);
kk++;
j = kk - 25*(kk/25);

if(rlf>maxlf) maxlf = rlf;
if(rlf<minlf) minlf = rlf;
alf += rlf;

FmtFile(hdl,"\n %d[w3] %f[p2] %f[p2] %d %f[p4]
%f[p4] %f[p2] %f[p2]",kk,uamp/s,freq,samp,rlf*100.,phd-
vphs,iamp,uamp/ratio);
```



```
        FmtOut("\n %d[w3]  %f[p2]  %f[p2]  %d  %f[p4]  %f[p4]
%f[p2]  %f[p2]",kk,uamp/s,freq,samp,rlf*100.,phd-
vphs,iamp,uamp/ratio);

        if(j==0) FmtOut("\n");

    }

    alf=alf/kk;
    FmtFile(hdl,"\n =====");
    FmtFile(hdl,"\n\nThe average value of L.F. over %d measurements
%f[p4]",
    kk,alf*100.);
    FmtFile(hdl,"\nMax. L.F.: %f[p4],    Min. L.F.
%f[p4]",maxlf*100.,minlf*100.);
    FmtFile(hdl,"\n\nDate: %s\tTime: %s\n\r", DateStr (), TimeStr
());
    FmtOut("\n =====");
    FmtOut("\n\nThe average value of L.F. over %d measurements
%f[p4]",
    kk,alf*100.);
    FmtOut("\nMax. L.F.: %f[p4],    Min. L.F.
%f[p4]",maxlf*100.,minlf*100.);
    FmtOut("\n\nDate: %s\tTime: %s\n\r", DateStr (), TimeStr ());

    CloseFile (hdl);
}
```



Program 2 Dissipation factor measurement with the TDS-540 Digital Oscilloscope and GPIB-488.2

```
, *****  
'The program is for data acquiring and dissipation factor  
'calculation through the TDS-540 digital oscilloscope.  
' Run environment: LabWindow 2.1  
' Analog input: channel 1 and channel 2 (-5V - +5V)  
, *****
```

```
REM $INCLUDE: 'qbdecl.bas'
```

```
REM $INCLUDE: 'gpibio.bas'
```

```
' Assign a unique identifier to the gpib board (assumed to be board  
GPIB0)
```

```
' and store in variable BRD; check for errors
```

```
'
```

```
CLS
```

```
PRINT:PRINT
```

```
PRINT " (TDS 540 - GPIB) LF Program "
```

```
PRINT " *****"
```

```
PRINT
```

```
PRINT " *** Connect your test signals to Channel 1 AND
```

```
2 ***"
```

```
PRINT
```

```
print " Current -> Ch1 • Voltage -> Ch2"
```

```
print
```



```
PRINT "          Please turn on the OSCILLOSCOPE and SIGNAL
SOURCES          "
PRINT
PRINT "          IMPORTANT ..... Make sure your SETTINGS are as
below ( 1 cycle) "
PRINT
PRINT "          SETUP #      SAMPLING RATE      POINTS ON SCOPE      POINTS
TO BE ACQUIRED"
PRINT "          4          250 KS/S          5000
4166"
PRINT "          3          100          2500
1666 "
PRINT "          2          50          1000
833  "
PRINT "          1          25          500
416  "

PRINT
INPUT " How many points are you going to acquire (Max:4166):";
RL%
' PRINT
' PRINT "    *** Press any key when done ";
' ANS$ = INPUT$(1)

PI! = 3.141592654#
GPIBNAME$ = "GPIB0"
CALL IBFIND(GPIBNAME$, BRD%)
IF BRD% < 0 THEN PRINT "BAD IBFIND GPIB BOARD CALL": STOP
'
' Assign a unique identifier to device (assumed to be device DEV1)
and store
' in variable SCOPE; check for errors
'
BDNAME$ = "DEV1"
CALL IBFIND(BDNAME$, scope%)
IF scope% < 0 THEN PRINT "BAD IBFIND DEVICE CALL": STOP
'
```



```
' TO GET CURRENT SIGNALS
*****
' *** *** ***
' Clear the device and check for errors
'
' CALL IBCLR(scope%)
' IF IBSTA% < 0 THEN PRINT "BAD IBCLR CALL": STOP
' CALL IBSRE(BRD%, 0)
' IF IBSTA% < 0 THEN PRINT "BAD IBSRE CALL": STOP
'
' Turn off the header from query responses.
'
' CALL GPIBWRITE(scope%, "HEADER OFF")
'
' Set up the data source to be channel 1.
'
' DATSRC$ = "CH1"
' WRT$ = "DATA:SOURCE " + DATSRC$
' CALL GPIBWRITE(scope%, WRT$)
'
' Set up data encoding to be ribinary and data width to 1.
'
' CALL GPIBWRITE(scope%, "DATA:ENCDG RIBINARY;WIDTH 1")
'
' Print a message on the screen instructing the user to connect
Channel 1
' to the test signal.
'
'
' Set up the recordlength, and the data start and data stop
positions.
' In this example, the entire waveform is obtained so data start
and
' data stop are 1 and 500 respectively.
'
' RL% = 1666
' WRT$ = "HORIZONTAL:RECORDLENGTH " + STR$(RL%)
```



```
CALL GPIBWRITE(scope%, WRT$)
DSTART% = 1
DSTOP% = RL%
WFPOINTS% = DSTOP% - DSTART% + 1
PRINT : PRINT : PRINT
PRINT "          Number of waveform points is "; WFPOINTS%
PRINT
WRT$ = "DATA:START " + STR$(DSTART%)
CALL GPIBWRITE(scope%, WRT$)
WRT$ = "DATA:STOP " + STR$(DSTOP%)
CALL GPIBWRITE(scope%, WRT$)
WRT$ = "HEADER OFF"
CALL GPIBWRITE(scope%, WRT$)

'
'
' Make sure setup changes have taken effect and a new waveform is
acquired
'
'          CALL GPIBWRITE(scope%, "ACQUIRE:STATE RUN")
'
' Wait for the scope to acquire the waveform.
'
'          CALL GPIBWAITCOM(scope%, 14)
'
' Send the scope a curve query to get waveform data.
'
'          CALL GPIBWRITE(scope%, "CURVE?")
'
'
' Read waveform data.
'
' The waveform is formatted as #<x><yyy><data><newline> where
'   <x> is the number of y bytes; for example if yyy = 500, then
'       x = 3
'   <yyy> is the number of bytes to transfer including checksum;
'       if width is 1 then all bytes on bus are single data
'       points; if width is 2 then bytes on bus are
'       2-byte pairs; this program uses width of 1
```



```
'      <data> is the curve data
'      <newline> is a single byte newline character at the end of
the data
'
      RLPREAM$ = SPACE$(LEN(STR$(WFPOINTS%)) + 1)
      CALL GPIBREAD(scope%, RLPREAM$)
'
'
'      Dimension the array. There are two data points stored in each
array element.
'      The first data point is stored in the low byte and the second
data point is
'      stored in the high byte. The array dimension is one-half the
number of
'      waveform points plus one additional element. This last element is
used for
'      the termination character and, optionally, a data point if the
waveform
'      contains an odd number of points.
'
      IARRDIM% = INT(WFPOINTS% / 2) + 1      ' 2 data points per
integer
      CURBYTES% = WFPOINTS% + 1      ' set up the number of bytes
to read
      DIM IARR%(IARRDIM%)      ' set up the storage array
'
'
'      Read in the waveform data
'
      CALL IBRDI(scope%, IARR%(), CURBYTES%)
      IF IBSTA% < 0 THEN PRINT "BAD CURVE DATA REQUEST": STOP
      MASK% = &H100
      CALL IBWAIT(scope%, MASK%)
      IF IBSTA% < 0 THEN PRINT "BAD CURVE DATA READ": STOP
'
'
'      Transfer data to another array that will have one data element
per data
```



```
point to make data manipulation easier. The low byte, high byte
swapping
' and sign extension of the storage mechanism is also handled.
'
' Check to see if the number of bytes in the waveform is even or
odd to
' determine how the last data point and newline character are
stored.
' The data is also written to a file called "WFM".
'

    IF INT(WFPOINTS% / 2) = WFPOINTS% / 2 THEN WFPTODD% = 0 ELSE
WFPTODD% = 1
    LASTEL% = IARRDIM% - 1
    DIM WFARR%(WFPOINTS%) ' set up the waveform output array
    FOR I% = 0 TO LASTEL%
        IF I% = LASTEL% AND WFPTODD% = 0 THEN EXIT FOR
        P% = IARR%(I%) AND 255
        IF P% < 128 THEN WFARR%(2 * I%) = P% ELSE WFARR%(2 * I%)
= -(256 - P%)
        IF I% = LASTEL% AND WFPTODD% = 1 THEN EXIT FOR
        P% = (IARR%(I%) AND -256) / 256
        IF P% < 128 THEN WFARR%(2 * I% + 1) = P% ELSE WFARR%(2 *
I% + 1) = -(256 - P%)
    NEXT I%
'
'
' Read the waveform preamble.
' Get the vertical offset and scale multiplier,
' the trigger point, the horizontal sampling interval
' and the horizontal units to convert the data points to
' time and voltage values.
'

    WRT$ = "WFMPRE:" + DATSRC$ + ":YOFF?"
    CALL GPIBWRITE(scope%, WRT$)
    RD$ = SPACE$(20)
    CALL GPIBREAD(scope%, RD$)
    YOFF! = VAL(RD$)
    WRT$ = "WFMPRE:" + DATSRC$ + ":YMULT?"
```



```
CALL GPIBWRITE(scope%, WRT$)
RD$ = SPACE$(20)
CALL GPIBREAD(scope%, RD$)
YMULT! = VAL(RD$)
WRT$ = "WFMPRE:" + DATSRC$ + ":YUNIT?"
CALL GPIBWRITE(scope%, WRT$)
YUNIT$ = SPACE$(20)
CALL GPIBREAD(scope%, YUNIT$)

WRT$ = "WFMPRE:" + DATSRC$ + ":PT_off?"
CALL GPIBWRITE(scope%, WRT$)
RD$ = SPACE$(20)
CALL GPIBREAD(scope%, RD$)
Ptoff! = VAL(RD$)
WRT$ = "WFMPRE:" + DATSRC$ + ":XINCR?"
CALL GPIBWRITE(scope%, WRT$)
RD$ = SPACE$(20)
CALL GPIBREAD(scope%, RD$)
XINCR! = VAL(RD$)
WRT$ = "WFMPRE:" + DATSRC$ + ":XUNIT?"
CALL GPIBWRITE(scope%, WRT$)
XUNIT$ = SPACE$(20)
CALL GPIBREAD(scope%, XUNIT$)

' $$$
'      Output header (x-, y-units, date, time and source)
'      Write out the data to a file DEFINED BELOW
'      INPUT "PLEASE INPUT THE OUTPUT FILENAME"; WAVEFL$ ' set up
an output file for the data time and voltages
      WAVEFL$ = "test.out" ' set up an output file for the data
time and voltages
      OPEN WAVEFL$ FOR OUTPUT AS #1
'      PRINT #1, USING "\\ "; XUNIT$; " ";
'      PRINT #1, USING "\  "; YUNIT$; " ";
'      PRINT #1, "CH1"
'
'
'      Process waveform data.
```



```
'      Write out the data to a file called "WFM_DATA.PRN".
'
      DIM CURTARR!(WFPOINTS%) ' set up the voltage output array
      DIM TIMEARR!(WFPOINTS%) ' set up the time output array
      FOR I% = 0 TO WFPOINTS% - 1
          TIMEARR!(I%) = (I% - Ptoff!) * XINCR!
          CURTARR!(I%) = (WFARR%(I%) - YOFF!) * YMULT!
      PRINT TIMEARR!(I%), ",", CURTARR!(I%)

      NEXT I%

      *** CURTARR!(I%) ***

      TO GET VOLTAGE SIGNALS
      *****
      *** *** ***
      Clear the device and check for errors

      CALL IBCLR(scope%)
      IF IBSTA% < 0 THEN PRINT "BAD IBCLR CALL": STOP
      CALL IBSRE(BRD%, 0)
      IF IBSTA% < 0 THEN PRINT "BAD IBSRE CALL": STOP

      Turn off the header from query responses.

      CALL GPIBWRITE(scope%, "HEADER OFF")

      Set up the data source to be channel 2.

      DATSRC$ = "CH2"
      WRT$ = "DATA:SOURCE " + DATSRC$
      CALL GPIBWRITE(scope%, WRT$)

      Set up data encoding to be ribinary and data width to 1.

      CALL GPIBWRITE(scope%, "DATA:ENCDG RIBINARY;WIDTH 1")

      Print a message on the screen instructing the user to connect
Channel 1
      to the test signal.
```



```
'  
'  
'  
' Set up the recordlength, and the data start and data stop  
positions.  
' In this example, the entire waveform is obtained so data start  
and  
' data stop are 1 and 500 respectively.  
'  
'      RL% = 1666  
      WRT$ = "HORIZONTAL:RECORDLENGTH " + STR$(RL%)  
      CALL GPIBWRITE(scope%, WRT$)  
      DSTART% = 1  
      DSTOP% = RL%  
      WFPOINTS% = DSTOP% - DSTART% + 1  
'      PRINT : PRINT : PRINT  
'      PRINT "          Number of waveform points is "; WFPOINTS%  
'      PRINT  
      WRT$ = "DATA:START " + STR$(DSTART%)  
      CALL GPIBWRITE(scope%, WRT$)  
      WRT$ = "DATA:STOP " + STR$(DSTOP%)  
      CALL GPIBWRITE(scope%, WRT$)  
      WRT$ = "HEADER OFF"  
      CALL GPIBWRITE(scope%, WRT$)  
'  
'  
' Make sure setup changes have taken effect and a new waveform is  
acquired  
'  
'      CALL GPIBWRITE(scope%, "ACQUIRE:STATE RUN")  
'  
' Wait for the scope to acquire the waveform.  
'  
'      CALL GPIBWAITCOM(scope%, 14)  
'  
' Send the scope a curve query to get waveform data.  
'  
      CALL GPIBWRITE(scope%, "CURVE?")
```



```
'  
'  
' Read waveform data.  
'  
' The waveform is formatted as #<x><yyy><data><newline> where  
'   <x> is the number of y bytes; for example if yyy = 500, then  
'       x = 3  
'   <yyy> is the number of bytes to transfer including checksum;  
'       if width is 1 then all bytes on bus are single data  
'       points; if width is 2 then bytes on bus are  
'       2-byte pairs; this program uses width of 1  
'   <data> is the curve data  
'   <newline> is a single byte newline character at the end of  
the data  
'  
      RLPREAM$ = SPACE$(LEN(STR$(WFPOINTS%)) + 1)  
      CALL GPIBREAD(scope%, RLPREAM$)  
'  
'  
' Dimension the array. There are two data points stored in each  
array element.  
' The first data point is stored in the low byte and the second  
data point is  
' stored in the high byte. The array dimension is one-half the  
number of  
' waveform points plus one additional element. This last element is  
used for  
' the termination character and, optionally, a data point if the  
waveform  
' contains an odd number of points.  
'  
      IARRDIM% = INT(WFPOINTS% / 2) + 1      ' 2 data points per  
integer  
      CURBYTES% = WFPOINTS% + 1      ' set up the number of bytes  
to read  
'      DIM IARR%(IARRDIM%)      ' set up the storage array  
'  
'
```



```
' Read in the waveform data
'
      CALL IBRDI(scope%, IARR%(), CURBYTES%)
      IF IBSTA% < 0 THEN PRINT "BAD CURVE DATA REQUEST": STOP
      MASK% = &H100
      CALL IBWAIT(scope%, MASK%)
      IF IBSTA% < 0 THEN PRINT "BAD CURVE DATA READ": STOP
'
'
' Transfer data to another array that will have one data element
per data
' point to make data manipulation easier. The low byte, high byte
swapping
' and sign extension of the storage mechanism is also handled.
'
' Check to see if the number of bytes in the waveform is even or
odd to
' determine how the last data point and newline character are
stored.
' The data is also written to a file called "WFM".
'
      IF INT(WFPOINTS% / 2) = WFPOINTS% / 2 THEN WFPTODD% = 0 ELSE
WFPTODD% = 1
      LASTEL% = IARRDIM% - 1
'      DIM WFARR%(WFPOINTS%) ' set up the waveform output array
      FOR I% = 0 TO LASTEL%
          IF I% = LASTEL% AND WFPTODD% = 0 THEN EXIT FOR
          P% = IARR%(I%) AND 255
          IF P% < 128 THEN WFARR%(2 * I%) = P% ELSE WFARR%(2 * I%)
= -(256 - P%)
          IF I% = LASTEL% AND WFPTODD% = 1 THEN EXIT FOR
          P% = (IARR%(I%) AND -256) / 256
          IF P% < 128 THEN WFARR%(2 * I% + 1) = P% ELSE WFARR%(2 *
I% + 1) = -(256 - P%)
      NEXT I%
'
'
' Read the waveform preamble.
```



```
' Get the vertical offset and scale multiplier,  
' the trigger point, the horizontal sampling interval  
' and the horizontal units to convert the data points to  
' time and voltage values.  
,
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":YOFF?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
RD$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, RD$)
```

```
YOFF! = VAL(RD$)
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":YMULT?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
RD$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, RD$)
```

```
YMULT! = VAL(RD$)
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":YUNIT?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
YUNIT$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, YUNIT$)
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":PT_Off?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
RD$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, RD$)
```

```
PtOff! = VAL(RD$)
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":XINCR?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
RD$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, RD$)
```

```
XINCR! = VAL(RD$)
```

```
WRT$ = "WFMPRE:" + DATSRC$ + ":XUNIT?"
```

```
CALL GPIBWRITE(scope%, WRT$)
```

```
XUNIT$ = SPACE$(20)
```

```
CALL GPIBREAD(scope%, XUNIT$)
```

```
,  
' Output header (x-, y-units, date, time and source)  
' Write out the data to a file called "WFM_DATA.PRN".
```



```
'      WAVEFL$ = "WFM_DATA.PRN"      ' set up an output file
for the data time and voltages
'      OPEN WAVEFL$ FOR OUTPUT AS #1
'      PRINT #1, USING "\\\"; XUNIT$; "  ";
'      PRINT #1, USING "\  \"; YUNIT$; "  ";
'      PRINT #1, "CH1"
'
'
'
'      Process waveform data.
'      Write out the data to a file called "WFM_DATA.PRN".
'
'
'      DIM VOLTARR!(WFPOINTS%) ' set up the voltage output array
'      DIM TMVARR!(WFPOINTS%) ' set up the time output array
'      FOR I% = 0 TO WFPOINTS% - 1
'          TMVARR!(I%) = (I% - Ptoff!) * XINCR!
'          VOLTARR!(I%) = (WFARR$(I%) - YOFF!) * YMULT!
'          PRINT TMVARR!(I%), ", ", VOLTARR!(I%)
'
'      NEXT I%
'
'      WFPOINTS%      *** CURTARR(I%) *** VOLTARR!(I%)***
'      *****
'      TO PERFORM THE CALCULATION OF DISSIPATION FACTOR BY USING
ABOVE TWO
'      ARRAYS -- CURTARR(I%) AND VOLTARR!(I%)
'      *****
'      PRINT " Data acquired, You may turn off SIGNAL SOURCES now"
'      PRINT " Calculating, Please wait ... .."
'      PRINT #1, DATE$, "      ", TIME$
'      SCREEN 12
'      WINDOW(0, -150) - (799, 150)
'      FOR I% = 0 TO WFPOINTS% - 2
'          LINE (I%, VOLTARR(I%)) - (I% + 1, VOLTARR(I% + 1))
'      NEXT I%
'
'
'      DIM IRE!(4), IIM!(4), URE!(4), UIM!(4), IAMP!(4), IANGLE!(4)
'      DIM PHD!(4), LOSF!(4), UAMP!(4), UANGLE!(4)
```



```
FOR I% = 0 TO 4
    IRE!(I%) = 0.
    IIM!(I%) = 0.
    URE!(I%) = 0.
    UIM!(I%) = 0.
NEXT I%
FOR J% = 0 TO 4
    FOR I% = 0 TO WFPOINTS% - 1
        WT! = I% * 2. * PI! * (2. * J% + 1.) / wfpoints%
        URE!(J%) = URE!(J%) + VOLTARR(I%) * SIN(WT!)
        UIM!(J%) = UIM!(J%) + VOLTARR(I%) * COS(WT!)
        IRE!(J%) = IRE!(J%) + CURTARR(I%) * SIN(WT!)
        IIM!(J%) = IIM!(J%) + CURTARR(I%) * COS(WT!)
    NEXT I%
    PRINT URE!(J%), UIM!(J%), IRE!(J%), IIM!(J%)
    PRINT
    UANGLE!(J%) = ATN(UIM!(J%) / URE!(J%))
    UAMP!(J%) = ABS((2. / WFPOINTS%) * URE!(J%) /
COS(UANGLE!(J%)))
    UANGLE!(J%) = UANGLE!(J%) * 180. / PI
    IANGLE!(J%) = ATN(IIM!(J%) / IRE!(J%))
    IAMP!(J%) = ABS((2. / WFPOINTS%) * IRE!(J%) /
COS(IANGLE!(J%)))
    IANGLE!(J%) = IANGLE!(J%) * 180. / PI
    IF (URE!(J%) <= 0.) THEN UANGLE!(J%) = 180. + UANGLE!(J%)
    IF (IRE!(J%) <= 0.) THEN IANGLE!(J%) = 180. + IANGLE!(J%)
    IF (ABS(IANGLE!(J%) - UANGLE!(J%)) <= 180.) THEN
        PHD!(J%) = IANGLE!(J%) - UANGLE!(J%)
    ELSE PHD!(J%) = 360. - ABS(IANGLE!(J%) - UANGLE!(J%))
    END IF
    LOSF!(J%) = TAN((90. - PHD!(J%)) * PI / 180.)
    PRINT IANGLE!(J%), UANGLE!(J%), PHD!(J%), LOSF!(J%)
NEXT J%
PRINT #1, "SAMPLES PER CHANNEL = ", WFPOINTS%
PRINT #1, "THE CURRENT MAG. = ", IAMP!(0), "    PHASE =
", IANGLE!(0)
PRINT #1, "THE VOLTAGE MAG. = ", UAMP!(0), "    PHASE =
", UANGLE!(0)
```



```
PRINT #1, "      ***"
PRINT #1, "THE PHASE DIFF. = "; PHD!(0)
PRINT #1,

cls
j%=0
FOR I%=0 TO 4
  if(uamp!(i%)>uamp!(0)*1.5/100.) then
    if(I%>2 and j%=0) then
      PRINT "      *** Press any key when done ";
      ANS$ = INPUT$(1)
      j%=1
    end if
    k%=2*i%+1
    print "
=====
="
      PRINT " The I mag.= ",iamp!(I%),"   phase =
",iangle!(I%)
      PRINT " The V mag.= ",Uamp!(I%),"   phase =
",Uangle!(I%)
      print
      print " The phase diff. of ";k%, " component was =
";phd!(I%)
      print " L.F.= ";lof!(I%)*100.,"%
      PRINT
      print #1, "
=====
="
      PRINT #1, " The I mag.= ",iamp!(I%),"   phase =
",iangle!(I%)
      PRINT #1, " The V mag.= ",Uamp!(I%),"   phase =
",Uangle!(I%)
      print #1,
      print #1, " The phase diff. of ";k%, " component was =
";phd!(I%)
      print #1, " L.F.= ";lof!(I%)*100.,"%
      PRINT #1,
```



```

        if(i%<>0 and losf!(i%)>0.) then
losf!(0)=losf!(0)+(uamp!(i%)/uamp!(0))^2*k%*LOSF!(I%)
        end if
    next i%
    print "
=====
="
    PRINT
    PRINT "THE LOASS FACTOR = ",LOSF!(0)*100.,"% "
    print #1, "
=====
="
    PRINT #1,
    PRINT #1,"THE LOASS FACTOR = ",LOSF!(0)*100.,"% "
    print
    #1,"=====
=====
'    print those two arrays to a file with name defined above
    print
    PRINT #1, "        CURRENT                VOLTAGE"
    FOR I%=0 TO WFPOINTS%-1
    PRINT #1, "        ";CURTARR!(I%), "        ", VOLTARR!(I%)
    NEXT I%
'
'
'    Final message
'
    PRINT "        Waveform current and voltage points are in file
";
    PRINT WAVEFL$
    PRINT
    END

```

' *****



```
' gpibio.bas - collection of input/output routines to be used by
the main program
' *****
'
' GPIBREAD - read into the string from the device and wait for the
read
' to finish.
'
SUB GPIBREAD(DEV%,RESP$) STATIC
CALL IBTMO(DEV%,13)
CALL IBRD (DEV%,RESP$)
IF IBSTA% < 0 THEN PRINT "BAD READ FROM SCOPE" : STOP
RDCHAR% = IBCNT%
MASK%=&H100
CALL IBWAIT(DEV%,MASK%)
IF IBSTA% < 0 THEN PRINT "BAD READ WAIT FROM SCOPE" : STOP
END SUB
'
'
' GPIBWRITE - send the contents of the string to the device and
wait
' for the write to finish.
'
SUB GPIBWRITE(DEV%,CMD$) STATIC
CALL IBTMO(DEV%,13)
CALL IBWRT (DEV%,CMD$)
IF IBSTA% < 0 THEN PRINT "BAD WRITE TO SCOPE" : STOP
WRTCHAR% = IBCNT%
MASK%=&H100
CALL IBWAIT(DEV%,MASK%)
IF IBSTA% < 0 THEN PRINT "BAD WRITE WAIT TO SCOPE" : STOP
END SUB
'
'
' GPIBWIAT - wait for a specified timeout to expire.
'
SUB GPIBWAIT(DEV%,DELAY%) STATIC
CALL IBTMO(DEV%,DELAY%)
```



```
MASK%=&H4000
CALL IBWAIT(DEV%,MASK%)
END SUB

'
'
' GPIBWIATCOM - wait for a gpib command to finish by doing a query
' and reading its results; wait only as long as the delay value.
'

SUB GPIBWAITCOM(DEV%,DELAY%) STATIC
CALL IBTMO(DEV%,DELAY%)
CALL GPIBWRITE(DEV%,"*OPC?")
RD$ = SPACE$(5)
CALL GPIBREAD(DEV%,RD%)
END SUB
```