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Measurement And Modeling Of Errors For Relaying Current Transformers And Voltage Transformers

by

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(ABSTRACT)

A measurement tool has been developed to estimate errors in relaying current transformers and voltage transformers. The tool has been developed to collect data in a substation and send it to a remote location over a telephone line. Different schemes were evaluated and tested in the laboratory. The final choice was made on the basis of the hardware and transmission cost constraints.

The measurement unit was developed using hardware similar to that used in a computer relay. The signals from the current and voltage transducers were sampled using a microprocessor and an analog to digital converter in real time. The measurement device has been installed in the field. The data from the field was collected remotely and analyzed in the Virginia Tech Power Systems laboratory. The analysis of the data is presented at the end.

Acknowledgements

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I would like to thank American Electric Power Corporation and the Appalachian Power Company for allowing me to install and operate the project at the Cloverdale Substation, Virginia.

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Chapter 1. Introduction

1.1 Problem definition:

The computer relays now being developed [2] are leading to new concepts in protection systems, which take advantage of the powerful computational capabilities inherent to any computer. These ideas, which cannot be implemented using conventional relays, are expected to broaden the scope and capabilities of future power system.

Computer relays use data in discrete format which can be easily processed. The relays take data from current transformers (CT) and voltage transformers (CVT). Normally, relaying CTs and CVTs have lesser accuracy than the metering CTs and CVTs [13,14,15,16]. In case of computer relays, if the error models for the relaying CTs and CVTs are known, the errors in measurements can be easily rectified. This can be done with addition of software to the existing relay software and without any kind of addition to the existing hardware used by the computer relays.

However the method relies on the assumption that the error models for the CTs and CVTs in question do not change over a period of time, or that the error models always follow a definite pattern. No data is currently available in support or in contradiction to this assumption. This is the first project in an attempt to collect such data to verify this assumption.

The goal of the project is to develop a tool which will calculate and monitor the errors in the relaying CTs and CVTs over a year. The errors would be compared with the metering CTs and CVTs.

The data collected by this tool represents the data collected by a computer relay. Therefore, the hardware and data collection rate should be close to that of a computer relay. The hardware for this tool was selected to be similar to the hardware used by a computer relay, which has been developed at the Virginia Tech Power Systems Laboratory [2].

1.2 Installation of Project

The Cloverdale substation of the Appalachian Power Company near Roanoke in Virginia is selected for the site of installation [3]. The current transformers are located on transformer no. 6A, which connects the 345 KV bus at the station to 500 KV line going to Dooms & Lexington. The transformer is rated at 200 MVA. The relaying CT (55) is on the 500 KV side of the transformer while the metering CT (98) is located on the 345 KV side of the transformer. The nominal ratio of the relaying CT is 240:1 and the nominal ratio of the metering CT is 1000:5.

The potential transformer (74) (metering class voltage transformer) is located on a tie connecting 345 KV bus no. 1, and 345 bus no. 2. The CCVT (58) is located on the 345 KV line going to Matt Funk. The bushing voltage transformer (75) is located on the tie connecting 345 KV bus no. 1 and 345 KV bus no. 2.

1.3 Organization of the thesis

Chapter 2 discusses the assumed error model, and the technique used for data collection. The errors in measurements would consist of a deterministic part and random noise. The random noise is assumed to be Gaussian white noise with zero mean.

Three components are proposed for the deterministic part of the error model. These are the instantaneous current " i " or the instantaneous voltage " v " , a constant error " c " , and the ambient temperature " t " . The Weighted Least Squares method was used to calculate the coefficients of the error model parameters.

Chapter 3 discusses the difficulties encountered and the solutions found during the development of this project. It also describes in brief the final algorithm used in the measurement tool.

Chapter 4 discusses the development of the software. Two programs were developed. One was used in the field computer, which is used to collect data from the field and to calculate the error model. The second program was used in the computer in the laboratory, which was used as a host computer to issue commands to the field computer. The host computer can collect the data from the field computer and also diagnose any failures in the field computer to some extent.

Chapter 5 describes the hardware used for the field computer and the host computer. The host computer can be any IBM/PC compatible machine. The field computer is built using a Prototek VME-bus chassis, a Motorola MVME 133 68020 CPU (central processing unit) board [5], and a Data Translation

DT-1402-16SE A/D (analog to digital converter) board [8]. A signal conditioner unit was used to interface the signals from the field and the field computer. Two modems were used in the project for communication [17]. The hardware is described in greater detail in this chapter.

Chapter 6 describes data collected on a typical day. It also shows the analysis of the data using several graphs. The analysis is done for different error parameters of each transducer. The results of the analysis are presented in this chapter.

Chapter 7 concludes the thesis and also discusses the improvements that can be made for future development.

Chapter 2. Error Model and Data Collection

2.1 Introduction

The error model selected for the relaying CT and CVTs is described in this chapter. Two possible methods to collect data from the transducers are discussed. Also the selection of the method to collect the data is discussed in view of the hardware environment.

2.2 *Error model*

The error model consists of a deterministic part and a random error. The deterministic error is modeled using three parameters which are listed below:

1. **Instantaneous current or voltage**: The flux in the core of a CT or CVT does not change linearly and depends upon the instantaneous current (in case of CT) and instantaneous voltage (in case of CVT). This means that the error in the CT or CVT will also depend upon the instantaneous current or voltage input. Also, there may be some nonlinearity in the hardware interface which connects the computer to the relay. For example, analog amplifiers in the signal conditioner and the A/D converter may not be linear, therefore the error in a CT or a CVT will depend upon the instantaneous current or voltage input.

2. **Constant error**: The CT and CVT outputs may have a d.c offset due to the d.c offset in signal conditioning amplifiers. This will lead to a constant error.

3. **Surrounding temperature**: The ambient temperature of CTs and CVTs may influence the measurement error. The capacitance of the capacitors used in the voltage divider (in case of CVTs) are known to be temperature sensitive.

In short the proposed error model can be summed up by these equations; for a current transformer $\varepsilon = a \times i + b \times t + c + \eta$ and for a voltage transformer $\varepsilon = a \times v + b \times t + c + \eta$, where the symbols are as defined below.

$\varepsilon =$ instantaneous error

$v,i =$ instantaneous input current or voltage (magnitude)

$a =$ error coefficient related to current or voltage

$t =$ ambient temperature in degrees Kelvin

$b =$ error coefficient related to the temperature

$c =$ constant error related to d.c offset

$\eta =$ random noise

The program for the error model calculates the error coefficients a,b,c and the variance σ of the random noise "η".

2.3 Technique for data collection

2.3.1 Hardware for the measurement tool.

A Motorola 68020 CPU is selected for the field installation [5]. An A/D board from Data Translation DT-1402-16SE is used for the analog to digital conversion [8]. An IBM PC machine acts as a host which will collect the data. The data was sent on a telephone line using Hayes Smartmodem 1200 [17]. The above hardware was selected since it is similar to the hardware used in computer relays being developed in the Virginia Tech Power Systems Laboratory.

2.3.2 Histograms

Initial Plan **:-**

Initially it was proposed that the data would be collected in the field over a day. Then it would be condensed with a minimal loss of information and sent to the host for further calculation of the error coefficients. It was proposed that histograms of the instantaneous currents and voltages of the relaying class CTs and CVTs would be collected in the field, corresponding to the instantaneous currents and voltages of the instrumentation class CT and CVT.

In a histogram there would be counters in the memory of the field computer, corresponding to every possible absolute error in current or voltage magnitudes. The A/D converter used in this project is a 12 bit signed converter, so that it can produce values ranging from -2048 to +2047 [8]. Therefore, we would require 2048 memory blocks. Each block would be located in the memory of the CPU according to the magnitudes of all possible currents and voltages in instrumentation CT and CVT. Every block will have a predetermined number of counters. Each counter will represent a predetermined absolute error between a preselected pair of transducers. This could be implemented by using a memory mapping table, which will map all counters representing a predefined amount of absolute error into the processor RAM (random access memory). This is illustrated further in figure 1.

As shown in figure 1, Block B represents a current value of 200 in the metering CT, and Block A represents a current value of 100 in the metering CT. It is assumed that the absolute error in the relaying CT will not exceed 10 % of the true value, therefore the number of counters in Block B are 41. The first counter represents zero error, the next 20 counters represent a positive error, and the following 20 counters represent negative errors. The Block A has only 21 counters, since it represents a current value of 100.

To illustrate this concept further, assume that the measurement unit takes a reading. The metering CT measures 200 units of current and the relaying CT also measures the same, then the counter B1 will get incremented by one. If the relaying CT measures 201 units of current the counter B2 will get incremented by one. On the other hand, if the relaying CT measures 199 the counter 21 will get incremented by one.

A preliminary study showed that this method could condense the collected data very efficiently preserving all of the significant information. But this method had its drawbacks. The main constraint was the on-board RAM available to the Motorola CPU [5].

In this method it had to be assumed, that errors in the relaying transducers would never go beyond certain percentage e.g 10 % of the true value (measurement made by the metering transducers). Although this kind of assumption is good as it would reject bad data, it created complications in terms of memory allocation for the data counters. For an assumption that the error will always be less than 10 % of the true value, the number of counters exceeded the memory available on the Motorola CPU board. This made it necessary to reduce the resolution of the A/D converter from 12 bits to 10 bits. However this would affect the accuracy of the measurement. If we wanted to keep the resolution of the A/D converter intact, we would have to assume that the absolute error is always less

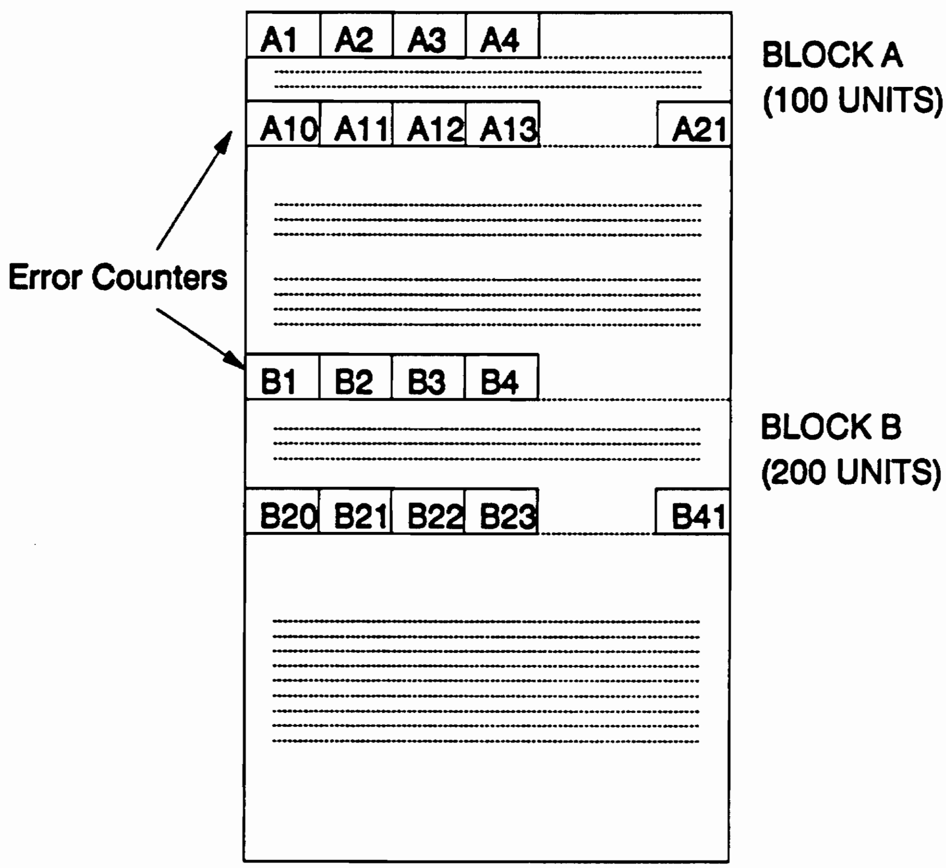

Figure 1. Arrangement of error counters in the memory.

than 1.8 % of the true value. This would have made the error parameters very biased.

Even with such modifications the histogram required large memory space. This meant very costly transmission of data to the host. In the worst case, the histogram would get filled up in four minutes and it would take approximately 1.55 seconds to send the data to the host (at 1200 baud and taking into account all the necessary handshaking signals). Therefore, in the worst case we would require a dedicated telephone line to collect the data.

The histogram had further limitations in terms of storing data according to changes in temperature. It could have maximum of only ten sets of data, each corresponding to a different temperature. This would have restricted the dynamic range of the temperature which in turn would have biased the coefficient of temperature in the error model.

Final selection of the method :-

Due to the problems mentioned above, it was decided that instead of condensing the data in the field computer, the error model would be calculated in the field itself and only the coefficients of the error parameters would be sent to the host.

This led to the selection of the "Weighted Least Squares" method for calculation of the error models [1]. The weight for each sample value was selected as

1.0 since all samples were considered equally important. The theory behind this method is briefly explained in the next section.

2.3.3 Theory of the Weighted Least Squares method

Let us write the error model equation $\varepsilon = a \times i + b \times t + c + \eta$ in summation form, as explained in chapter 1.

$$d(k) = \sum_{i=1}^{n} [\, a_i f_i\,(k)] + \eta(k) \text{ where}$$

k = sample number

$d(k)$ = error for the k^{th} sample

n = number of error parameters or functions

a_i = coefficient for the i^{th} error parameter

f_i = i^{th} error parameter or function

$\eta(k)$ = random noise in k^{th} sample

From the above equation we get $\eta(k) = d(k) - \sum_{i=1}^{n}[\, a_i \, f_i \,(k)]$ and we have to estimate parameters a_i to minimize $\eta^2(k)$

The above problem can be rewritten as a minimization problem in vector form as shown below. Let J be a cost function.

$$J = \frac{1}{2} [\, \vec{D}^T - \vec{A}^T \vec{R}\,] \; \vec{W}\vec{W}^T \; [\, \vec{D}^T - \vec{A}^T \vec{R}\,]^T$$

where

$$\vec{A} = \begin{bmatrix} a_1 \\ a_2 \\ \cdot \\ \cdot \\ \cdot \\ a_n \end{bmatrix}$$

$$\vec{D} = \begin{bmatrix} d(1) \\ . \\ . \\ . \\ d(K) \end{bmatrix}$$

$$\vec{R} = \begin{bmatrix} f_1(1) & \dots f_1(K) \\ f_2(1) & \dots f_2(K) \\ & \dots \\ & \dots \\ f_n(1) & \dots f_n(K) \end{bmatrix}$$

$$\vec{W} = \begin{bmatrix} w(1) & & \\ & \ddots & \\ & & w(N) \end{bmatrix}$$

and J is the scalar cost function to be minimized.

For minimization of the error, we have to take a derivative of J and set it to zero. The derivation is shown below.

$$-\ [\vec{R}\,\vec{W}\,\vec{W}^T\,\vec{D}\,] + [\vec{R}\,\vec{W}\,\vec{W}^T\,\vec{R}^T\,\vec{A}\,] = \vec{0}$$

$$[\vec{R}\,\vec{W}\,\vec{W}^T\,\vec{R}^T\,\vec{A}\,] = [\vec{R}\,\vec{W}\,\vec{W}^T\,\vec{D}\,]$$

$$\vec{A} = [\,\vec{R}\,\vec{W}\,\vec{W}^T\,\vec{R}^T\,]^{-1}\,[\,\vec{R}\vec{W}\,\vec{W}^T\,\vec{D}\,]$$

For our problem, K = number of samples collected during a day and N = three i.e the number of parameters. Also the weighing matrix $\vec{W}$ is an identity matrix in this problem, therefore the equation reduces to

$$\vec{A} = [\,\vec{R}\,\vec{R}^T\,]^{-1}\,[\,\vec{R}\,\vec{D}\,]$$

Where $\vec{A}$ is the estimate of the error coefficients. The equation can be regrouped and written in following manner.

$$\vec{A} = \vec{F}^{-1}\,\vec{G}$$

The vectors $\vec{A}$,$\vec{G}$ and the matrix $\vec{F}$ are expressed in a compact form as follows.

$$\vec{A} = \begin{bmatrix} c \\ b \\ a \end{bmatrix}$$

$$\vec{F} = \begin{bmatrix} NN & NI & NT \\ NI & II & IT \\ NT & IT & TT \end{bmatrix}$$

$$\vec{G} = \begin{bmatrix} ND \\ DI \\ DT \end{bmatrix}$$

where

NN is the total number of samples collected for the relaying class transducer

NI is the sum of the currents or voltages collected from metering class transducers

NT is the sum of the temperature readings

II is the sum of the squares of the voltages or currents of the metering class transducer

TT is the sum of the squares of the temperature readings

ND is the sum of the differences between metering class and relaying class transducers

DI is the sum of the product of the metering class current or voltage readings and the corresponding errors in the relaying class readings

DT is the sum of the products of the temperature readings and the errors in measurements in the relaying class transducers

a is the coefficient of error parameter "i" i.e instantaneous current or voltage

b is the coefficient of error parameter "t" i.e the outside temperature

c is the constant error

The mean of the random noise and variance σ can be easily calculated, after solving for the vector $\vec{A}$.

Let us define two additional variables **ME and VR** where

ME is the sum of all errors in each channel e.g for CCVT channel ME is the sum of all recorded differences between metering transformer and the CCVT.

VR is the sum of squares of all errors in each channel.

The general derivation valid for all channels is as shown below.

$$ME = \sum_{i=1}^{K} \varepsilon_i$$

$$ME = \sum_{i=1}^{K} [\, a \times i_i + b \times T_i + \eta_i]$$

$$ME = \sum_{i=1}^{K} a \times i_i + \sum_{i=1}^{K} b \times T_i + \sum_{i=1}^{K} C_i + \sum_{i=1}^{K} \eta_i$$

$$ME = a \times \sum_{i=1}^{K} i_i + b \sum_{i=1}^{K} T_i + c \sum_{i=1}^{K} 1 + \sum_{i=1}^{K} \eta_i$$

$$ME = a \times NI + b \times NI + c \times NN + \sum_{i=1}^{K} \eta_i$$

Mean of the noise $= E(\eta) = \frac{\sum_{i=1}^{K} \eta_i}{K}$

Therefore the mean of noise is as given below.

Mean $= ME - a \times NI - b \times NT - c \times \frac{NN}{NN}$ since $K = NN$

The derivation for the standard deviation is as follows. $VR = \sum_{i=1}^{K} (\varepsilon_i)^2$

$$VR = \sum_{i=1}^{K} [ai_i + bT_i + c + \eta_i]^2$$

$$VR = \sum_{i=1}^{K} \{a^2 i_i^2 + b^2 T_i^2 + c^2 + 2[abi_i T_i + aci_i + bcT_i] + 2\eta_i[ai_i + bT_i + c] + \eta_i^2\}$$

$$VR = a^2\sum_{i=1}^{K} i_i^2 + b^2\sum_{i=1}^{K} T_i^2 + c^2\sum_{i=1}^{K} 1 + \sum_{i=1}^{K}\eta_i^2 + 2\{ab\sum_{i=1}^{K} i_i T_i + ac\sum_{i=1}^{K} i_i + bc\sum_{i=1}^{K} T_i + \sum_{i=1}^{K}\eta_i[ai_i + bT_i + c]\}$$

In the above equation η_i is much smaller than the deterministic error $ai_i + bT_i + c$ Therefore the product $\eta_i[ai_i + bT_i + c]$ is very small. Also $E[\eta_i]$ is zero, since the d.c offset is modeled by "c " , therefore the last term in the above equation $\sum_{i=1}^{K}\eta_i[ai_i + bT_i + c]$ is assumed to be zero. Therefore the equation reduces to

$$\sum_{i=1}^{K}\eta_i^2 = VR - a^2\sum_{i=1}^{K} i_i^2 - b^2\sum_{i=1}^{K} T_i^2 - c^2\sum_{i=1}^{K} 1 - 2ab\sum_{i=1}^{K} i_i T_i - 2ac\sum_{i=1}^{K} i_i - 2bc\sum_{i=1}^{K} T_i$$

This equation can be written in the variables explained above as follows.

$$\sum_{i=1}^{K}\eta_i^2 = VR - a^2 II - b^2 TT - c^2 NN - 2abIT - 2acNI - 2bcNT$$

The variance $E[\eta^2] = \frac{\sum_{i=1}^{K}\eta_i^2}{K}$

$$E[\eta^2] = \frac{VR - a^2II - b^2TT - c^2NN - 2abIT - 2acNI - 2bcNT}{NN} \text{ since K = NN.}$$

Therefore the standard deviation is as given below

$$\sigma = \sqrt{\frac{VR - a^2II - b^2TT - c^2NN - 2abIT - 2acNI - 2bcNT}{NN}}$$

The main advantage of this method is that the matrix $\vec{F}$ can be calculated on line, and the matrix inversion and matrix multiplications can be carried out off line, for the final solution. Also, except for the final division required to be carried out, all the operations are multiplications, additions, or subtractions. These operations can be carried out in the field computer without loosing any precision.

2.3.4 Verification of the least squares method

Before accepting this method it was tested extensively using computer simulations. The data samples were generated assuming some fixed values for the coefficients of the error parameters. Also Gaussian white noise was added to the samples. The method was tested with different values of the coefficients and the variance of the noise. These samples were processed using the method described above, and the coefficients of the error parameters were calculated. These coefficients were compared with the actual coefficients. The results obtained were close to the actual parameters and the method worked as expected. As an example a test result is given below.

In the following example the samples were calculated using double precision. Then they were converted into integers before starting the calculation of the errors, since the field computer reads data in integers. The samples were in the range of ±200. In all 1000 samples were taken. For the generation of the samples with errors (representing relaying CTs and CVTs), the base values or the true values (representing metering CTs and CVTs) were selected in the range of ±200. The base values were selected randomly using "random number generation" program on MicroVAX Fortran [12].

2.3.4.1 Example

Input parameters

$a = 0.15$

$b = 0.09$

$c = 2.0$

$\sigma = 1.5$

Calculated parameters

$a = 0.150299$

$b = 0.089336$

$c = 1.992748$

$\sigma = 1.502702$

mean = 7.455565 E -34

The variance and the mean were also calculated using all the samples. The results obtained are given below.

True mean and variance of the samples

mean = − 1.533457 E -31

$\sigma = 1.502702$

Chapter 3. Development and Implementation

3.1 Introduction

This chapter explains the various features introduced in the program to overcome problems encountered during the course of the project. It describes the phase compensation among certain channels and the removal of the third harmonic content from the voltage channels.

3.2 *Phase difference compensation*

In general, the signals from different channels will not be in phase. The phase differences may be present due to difference in parameters of each transformer and the phase differences in the signal conditioning filters. This means that when we compare the measurements of a the relaying current transformer with metering current transformer, the error in the measurement will be partly due to the phase differences between the two channels. This error is deterministic and should be deleted in order to get a correct estimate of the noise in the error model. The same thing is true in case of voltage transformers. The following scheme is implemented to compute and to compensate for this phase difference.

First the phase differences of the related channels are calculated using Discrete Fourier Transform. A 12 sample DFT algorithm is used, since the sampling frequency is 720 Hz [2]. Next, the phase differences are compensated for by sampling the related channels at different times instead of at the same instant. i.e we actually shift the lagging signal forward in time to coincide with the leading signal. This is illustrated in figure 2.

As shown in the figure 2, the signal from the channel of CCVT is lagging the metering PT signal by 5 electrical degrees. Each channel is sampled separately. The taller sampling pulses are for the PT while the shorter pulses are for the

CCVT. Different heights are used only for the purpose of clarity. The phase difference is compensated by sampling the CCVT channel 92.59 *μseconds* after sampling the PT channel. This is because 5 electrical degrees for a 60 Hz signal is equivalent to 92.59 *μseconds* in time.

The time delay is generated in the software using different wait loops, having different weights of time, i.e. one wait loop may represent 0.5 degrees per loop while another wait loop may represent 4 minutes per loop. The combination of these loops produces delays which are close to the actual phase difference.

In the final program there are two wait loops. The first wait loop with longer delay produce about 0.5 degree per loop i.e about 23.15 *μseconds* . The second wait loop is faster and has a resolution of about 2.4 minutes i.e 0.32 *μseconds* of delay per loop. The faster wait loop has a dynamic range of about 0.75 degree. This means that the faster loop can produce a maximum of 34.7 *μseconds* of delay. This enables us theoretically to match the related channels within 2.5 minutes of phase differences. However the phasor measurements using 12 sample DFT itself has computational errors which introduce error in calculation of phase differences. Also, the signal conditioner has active elements which can introduce varying phase differences. Therefore, in reality, the channels cannot be matched to within 2.5 minutes.

During the field tests it was found that the channels can be matched always within 8 minutes and sometimes within 4 minutes. This means that the maximum error introduced in 4 a volts rms signal due to phase difference is 13 millivolts, which is equivalent to 2 A/D converter count (+10 V is equal to 2047 A/D count). The maximum error occurs at zero crossing when the rate of change of the voltage or current is maximum. The error due to phase difference at the peak of the signal however is only 15 microvolts, which is insignificant. Therefore the overall error due to phase difference can be assumed to be zero. In the laboratory testing the channels could always be matched to within 4 minutes. This was possible since the environment is less noisy in the laboratory.

The project was completed using the above scheme, and was taken to the field in the Fall of 1988 for testing. After several tests some corrections were made in the software as well as in the hardware. Also some additional features were introduced for practical reasons. For example, the station computer answers the phone only after 10 rings, so that the normal use of the telephone line is not disturbed.

3.3 Removal of the third harmonic

After collecting and analyzing the data for three months, it was found that the voltage channels, i.e the CCVT and the Bushing VT showed exceptionally large variance of noise. To analyze this, some tables of raw data were collected

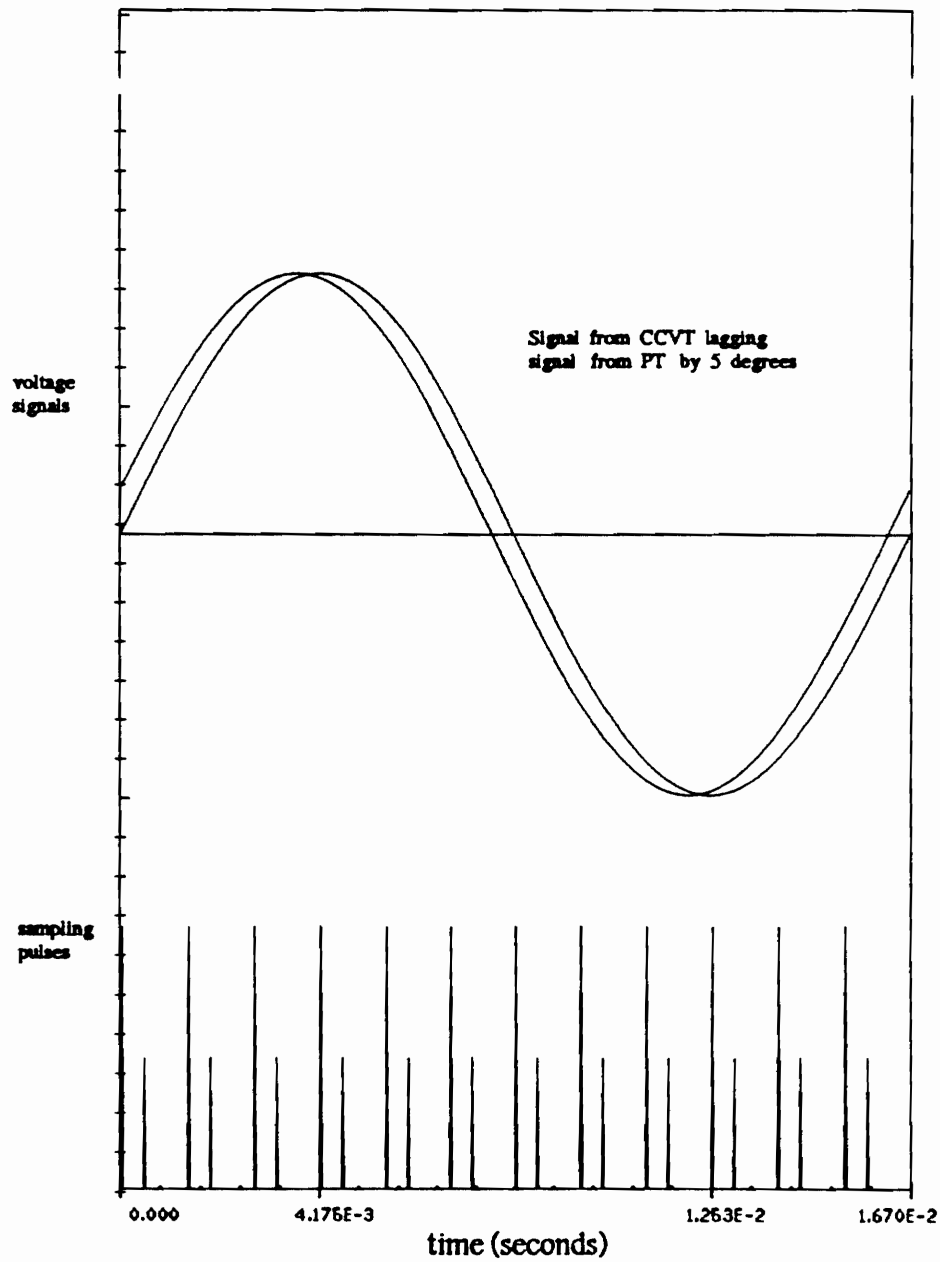

Figure 2. Phase difference compensation

and processed in the laboratory. It was found that the voltage channels contained large amounts of third harmonic, which were out of phase with each other.

Appendix A shows the raw data collected, i.e the actual samples taken in the field. These data are analyzed using DFT and the results of the different frequency content and the phases of each frequency for all channels are shown in figure 3. The different frequency contents are shown in magnitude and angle. The magnitude is measured in A/D converter count, while the angle is measured in degrees.

As shown in figure 3 the fundamental frequency is very well matched i.e there is hardly any phase difference between the channels as far as the fundamental is concerned. This is expected since the phase compensation scheme uses 12 sample DFT which will look at only the fundamental frequency of 60 Hz.

However the third harmonic shows phase differences among the voltage channels. This is probably due to the tuning circuit used in capacitive coupled voltage transformers. These LC circuits are tuned for 60 Hz and produce different phase differences for different frequencies. Therefore we cannot compensate the phase differences for all frequencies using the algorithm used above. The current channels as shown in the table do not have this problem.

Also from figure 3 we can see that the third harmonic content is much larger compared to the rest of the harmonics among the voltage channels. Therefore it was decided to get rid of this third harmonic content from these channels, before measuring the error parameters. The average of the third harmonic content was to be calculated over the day. The average was to be saved along with the error model for future use.

The final program was written using all these modifications and the unit was installed in the field for measurement in the Fall of 1989. The data collected from the field show some interesting trends which are discussed in chapter 6.

HARMONIC	METERING VT		CCVT		BUSHING VT	
	MAGNITUDE	ANGLE	MAGNITUDE	ANGLE	MAGNITUDE	ANGLE
1	1949.26	11.46	1975.18	11.44	1919.87	11.44
2	0.08	79.11	1.55	-9.28	0.44	161.30
3	23.75	-176.38	15.47	-158.52	12.21	122.06
4	0.70	-74.46	0.93	15.61	0.44	-35.60
5	0.51	-93.58	1.59	-46.03	1.58	-60.91
6	0.20	-90.00	0.20	90.00	0.07	90.00

HARMONIC	METERING CT		RELAYING CT	
	MAGNITUDE	ANGLE	MAGNITUDE	ANGLE
1	390.71	55.21	388.68	55.24
2	0.18	-145.00	0.21	-46.10
3	0.85	-165.14	0.64	-171.03
4	7.64	19.11	0.10	30.00
5	1.19	-58.39	1.58	-58.18
6	0.17	-90.00	0.20	-90.00

Figure 3. Fourier analysis of the raw data

Chapter 4. Software Development

4.1 Introduction

The following sections describe the various features of the software used in the field computer as well as in the host computer. The general organization of both programs is described in brief. The final section describes the working of the program in general.

4.2 Main features of software in the field computer

1. The program collects data from 2 CTs and 3 CVTs at the rate of 720 Hz, i.e for every channel it takes approximately 12 samples per cycle. It also reads outside temperature every time it takes the samples from the channels.

2. It dynamically calculates the phase difference between the related channels (i.e phase difference among the 3 CVTs and between the 2 CTs) and corrects the phase differences.

3. At the end of each day, or if requested by the host in the middle of a day, it can calculate the error model for the two relaying class CVTs and one relaying CT. For the calculation of the error model it considers variation in the temperature only if it is significant enough.

4. It stores the calculated error models in memory and sends them to the host whenever they are requested.

5. It can communicate with the host through a telephone line and in case of communication error it resumes the collection of data.

4.3 Main features of software in the host computer

1. The software is capable of connecting an IBM PC/AT or IBM PS/2 to a Hayes Smartmodem and program the modem to connect the PC to remote modem (modem at the site of installation), through a telephone line.

2. It is capable of dialing a telephone number provided by user. It can dial in both the " pulse " as well as the " touch tone " modes.

3. When the phone call ends, it disconnects the telephone line and resets the remote modem.

4. After connection is made to the remote modem, the program makes 10 tries to establish communication with the field computer.

5. The program is interactive in nature and will warn user if wrong answers are provided.

6. It is capable of collecting data from the field computer for any of the previous days.

7. It uses checksum to detect errors in communication. In case of communication error it can ask the field computer to send previous data again.

8. It can store the collected data on a diskette, if asked to do so by the user.

9. If requested by the user, it can command the field computer to process the collected data and to send the coefficients of the error parameters in the middle of a day.

10. It can also command the field computer to stop collecting the data for the day and to start a new day.

11. If requested by the user, the program can collect a table of raw data for diagnostic purposes. It can also get a log file, which contains the major phase compensations made during the day.

12. In case the communication link fails due to hardware failure, the program is able to recognize it and will abort the program. Also it is able to disconnect the telephone line before aborting.

4.4 Implementation of software in the field computer

The program is written in Motorola 68020 assembly language [5,6,7,8]. It is assembled using Microtec Research cross-assembler [4]. The program was written and developed on a MicroVAX II computer. The general organization and working of the program is described below in brief.

4.4.1 General organization of the program

4.4.1.1 Initialization

This part of the program defines addresses on the VME Bus for the variables and constants used in the program. This part also initializes a few variables, which are not initialized again unless the program is rebooted. The serial ports are configured in this part of the program. This configuration is never changed again. Also the parallel port of the DT-1402 (the A/D converter) is configured as an output port [8]. This part of the program also configures the modem for communication. The modem is also configured to answer the incoming call after 10 rings [17]. The program checks if the modem is connected before configuring it. In case the modem is not connected or is connected improperly the program will not run.

4.4.1.2 Resetting of memory

This part of the program clears the memory, used as work space. It may clear partial or full work space depending upon the status of the program. It also initializes counters and flags used in the main program. The timer interrupt is also initialized in this part.

4.4.1.3 Correction of phase differences

This part of the program collects the data from the CTs and CVTs. It determines the phase relations among the related channels and calculates software delays which will be introduced between the "sample and hold" signals to compensate for the phase differences. It also does the fine tuning of the delays. The data collected in this part of the program is not used for the calculation of the error model.

4.4.1.4 Collection of the data

This part of the program collects data from 2 CTs and 3 VTs with the phase corrections, and the outside temperature. This raw data is collected every 1.389 millisecond and stored in a table until it is full. The table length is such that the program can store data for half a minute.

4.4.1.5 Filtering of the collected data

This part of the program calculates the third harmonic content in the collected data, for each channel. It then removes this harmonic content from all voltage channels. The data for current transformers is not altered.

4.4.1.6 Calculation of coefficients of error model parameters

This part of the program calculates the coefficients of the error model using the collected data. It also stores the coefficients of each day in a cyclic table. The table can hold data for a maximum of 64 days.

4.4.1.7 Communication

This part of the program communicates with the host, whenever the host calls. It uses a dead-man timer to check for the failure of communication. In case of communication failure the program resumes the collection of data.

4.5 Implementation of the software in the host

The software is written in 8086 assembly language [9,11]. Before running the program, the user should make sure that the modem is connected to its serial port. The program is written to work on any IBM PC machine. The serial port "COM1" is used for the modem connection. If serial port "COM2" is used the same program can work, by changing the port addresses [10]. The general organization of the program is as described below.

4.5.1 Data file

When the program is first started, it will expect a diskette in the "B drive" of the PC. If the drive is empty or if the diskette is unformatted or if it is full, the program will put out a message saying so and will wait until the user provides a new diskette. If the diskette has any previous data files, it will open the old data file and the new data received from the field computer will be added at the end of the same file. In case the data file does not exist it will create a new data file "RECEIVE.DTA" and put out a message on the screen.

4.5.2 Dialing the remote modem

After opening the data file, the program sets the parameters of the modem and asks the user to type the phone number. Before typing the number the user should type "t" in case of a "touch tone" or "p" in case of a "pulse" telephone. The modem will dial the number and will connect the host to the remote modem.

4.5.3 Connecting to the field computer

After connecting to the remote modem, the host establishes contact with the field computer using handshaking characters. If the field computer acknowledges the call, the host will ask the field computer if it is ready to send the data. If the field computer is ready, the host will ask for the data and will collect the data. In case of an error in reception, the program will ask the user if he would like to receive the data again. If requested by the user, the host will command the field computer to send the same data again.

4.5.4 Saving the collected data

After reception of the data, the program provides an option to view the data on the screen. Next, if the user so requests, the program will write the data on the diskette. If the diskette is full, the program puts out a message saying so and waits until a new diskette is provided. The program saves the data in memory and when the new diskette is ready it writes the data on the diskette.

If the field computer has not processed the data for the day, and the user wants the field computer to process the data collected by that time, the host will command the field computer to process the data and to send the coefficients of the error model.

If the user wants the field computer to start collecting the data for a new day, the host program will command the field computer to do so.

The program also provides an option to collect data for any other day. If requested by the user the host asks the field computer what is the current day, and user can get data for any of the previous days. This is helpful since the user does not have to collect the data every day.

4.5.5 Diagnostic and log files

The host computer can diagnose the field computer to some extent. If requested by the user the program can collect 720 lines of raw data from the field computer. This can be used for later analysis. The user can also request a log file from the field computer. The file has the number of major phase compensations made during the day. The log file also saves the number of successful and unsuccessful calls made until that day.

4.5.6 Disconnecting the phone

After the call is finished, the program informs the field computer to end the call and then hangs up the phone.

Approximately 2 seconds are required for the actual transmission of the data. In case user requests to process the data in the middle of a day, the field computer will process it in less than 1 second. So, a normal call will not last for more than a few minutes.

4.6 Workings of the program

The program for field computer is stored in EEPROM (electrically erasable programmable read only memory) [5]. On power up the on board operating system 133-bug searches for this program, then loads the program into the onboard RAM. The program is then executed from the RAM.

The program generates 720 Hz sampling frequency using onboard timer and a software delay. More than 99.0 % of the period between any two sampling cycles is available for the collection, processing and storage of the data. The sampling frequency has an error of less than $\pm$ 93 ppm. The error is much less than that required for this application.

At the start of a day, the program calculates the phase differences between the related channels using, "12 sample Discrete Fourier Transform" (DFT) algorithm. Next it shifts the lagging signals in time, introducing 3 software delays between the related channels. The program again checks the phase differences between the related channels with the time shifts and makes fine adjustments in the three software delays. It carries out the fine tuning four times. If the 3 delays add up to more than 14 degrees (for 60 Hz frequency), i.e if the total delay adds up to more than 648 μ*seconds* or, if the phase difference is varying too rapidly the program will raise a flag to indicate that. After the initial correction of the phase differences, the program starts collection of data with the phase shift corrections. After every 120 cycles of samples (approximately 10 cycles of power frequency) the program goes back and rechecks the phase differences between the related channels. It again makes fine adjustments in the delays. These adjustments last for 12 cycles of the sampling frequency (about 1 cycle of the power frequency), unless the phase differences between the related channels change radically. In case the phase differences do change by a large amount, the software delays are recalculated from the start.

After collecting the samples the program partially processes the data and stores the processed data in memory. After that it checks if the host computer has called. If the host computer calls, the field computer temporarily suspends the collection of the data and answers the call.

At the end of each day the program calculates the coefficients of the error model for the two relaying CVTs and one relaying CT. The program stores these coefficients in the memory. The temperature variation is considered in the error model only if the variation is significant enough. If the temperature is not taken into account, it is indicated by raising a flag which would be sent to the host computer whenever data for the day is requested. In case the calculation runs into divide by zero error, the calculation is tried without temperature measurements. If the divide by zero error persists a flag is raised and stored along with the error parameters. The flags are sent to the host if the host requests data for that day.

If the host computer calls in the middle of a day, and gives command to calculate the error model using data collected until then, the computer in the substation calculates the error model. However, unless the host sends a command, the field computer does not assume that the current day is over and goes back to collect data to complete the day, after the call from the host ends. This allows the host to interrupt the substation computer and obtain the error models with lesser data. The host can also request data for any of the previous 64 days.

The program also controls the front panel indicator light. This light is kept flashing 2 times every second when the program is collecting the data. The light is flashed 4 times every second when the program is correcting for the phase differences among the related channels. The flashing of the light stops in case of malfunction in the program.

4.7 Tests on the program in the field computer

4.7.1 Test for the phase difference correction

The input to the signal conditioner (used in the laboratory) were taken from a signal generator at 60 Hz. Phase differences were introduced in the related channels using one stage RC filters. The r.m.s voltages of the related channels were kept equal (within a precision of ± 0.01 volts). The program was modified to store the actual voltage readings in memory. The program was run for several times and each time the voltage readings in memory were checked. The readings of the related channels were always found very close. The maximum difference was 6 A/D count i.e $\pm$ 0.029 volts. Most of the time the differences were less than 3 A/D count (+10 V is equal to 2047 A/D count).

In the second test, instead of instantaneous voltage samples, the phase differences were compared. For this experiment, the program was run for some minutes and then stopped. The phase differences of the related channels, stored in registers, were checked. The phase differences were always less than 3 minutes, which would produce a maximum error of ± 1 A/D count for a 4 volts r.m.s input. Most of the time the phase difference was between 1 to 2 minutes and sometimes less than 1 minute.

4.7.2 Test for measurement of the error coefficients

All the related subroutines (such as multiplication of 128 bit long word and 64 bit long word), were extensively tested as individual programs. After this all routines were put together and samples were generated inside the program itself using known error coefficients. For this the base values i.e samples representing metering CT and CVT were obtained by connecting a 60 Hz signal from the signal generator. After collecting a fixed number of sampled data, the program would calculate the error coefficients. Several tests were run for varying lengths of time, and every time the program calculated the coefficients correctly. The longest test time was over 24 hours. In this case no noise was added to the samples as it would take too long to compute it.

Example:

In this example, the d.c offset was taken to be 5 A/D count, the voltage coefficient was taken to be 0.4. No temperature measurements were taken and no noise was added. As a reference voltage, a 4 volts r.m.s signal at 60 Hz was taken from a signal generator. The measurements with the errors were calculated inside the field computer only for one channel. These measurements were then fed to the subroutine which calculates the error coefficients. The results obtained are as shown below:

Calculated	Actual
a = 0.3999	a = 4
c = 5.0000	c = 5
variance = 4.4721E-04	variance = 0

4.8 Tests on the program for host

In this case also all routines were tested individually. Since this program was mainly a communication program, it was tested along with the field computer. In this test the field computer was made to send predetermined numbers and the host had to receive them. The communication was also subjected to errors and failures to check whether field computer returns to collection of data, and whether the host computer disconnects the line correctly. All of these tests were also successful.

4.9 Final test in the laboratory

In this test the program was run for more than 24 hours. The input signals were taken from a signal generator at 60 Hz. Phase differences (ranging from 2 degrees to 6 degrees) were introduced in the related channels. The gains of the signal conditioners were adjusted so that the related channels had the same input voltages. The measuring unit was interrupted several times during the day and data was collected from it. Every time the program worked as expected. Later, the gains of the related channels were made different, a d.c offset was introduced in some of the channels, and the same test was run again. The measuring unit successfully calculated the error parameters during the tests. In these final tests temperature was kept zero by shorting the input channel for temperature.

4.10 Calibration in the field

Before installation the signal conditioner was calibrated in the field for some time. This was done by turning a switch on the back plate of the signal conditioner to " TEST " position. The switch in this position connects, the signal from the metering voltage transformer to all voltage transformer channels, and the signal from the relaying CT to both current channels. In this position, the same program in the field computer was run to find the errors in relaying CT and VTs, and compared with the metering CT and VT.

The calibration obtained from the field is shown in figure 4. The first coefficient of the relaying CT is about 0.779, which is very high. This is due to the fact that the input currents to the signal conditioner, coming from the relaying CT and the metering CT, have current ratio of 1:1.779. The ratio is due to the different turns ratios of the two CTs and also due to the fact that the CTs are located on different voltage sides of the line transformer. The voltage channels do not have any difference of transformer ratio. Therefore CCVT and Bushing VT should have their first coefficient equal to 0 in calibration.

The first coefficient of the CCVT and Bushing VT is of the order of 10^{-3}. The first coefficient of CT is 0.779 ± 0.001 Therefore the calibration of the signal conditioner is accurate upto the third decimal.

DATA FOR CCVT

DAY	NO. OF SAMPLES	VOLTAGE COEFFICIENT	TEMPERATURE COEFFICIENT (VOLTS/K)	CONSTANT (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)
0	62157769	0.1711E-02	-0.9456E-06	0.3212E-02	0.8950E-02	0.0000E+00
1	62156017	0.1711E-02	0.1670E-05	-0.1047E-01	0.9000E-02	0.0000E+00
2	62136817	0.1704E-02	0.4699E-06	-0.4154E-02	0.9063E-02	0.0000E+00
3	62103013	0.1709E-02	-0.1725E-06	-0.7843E-03	0.9155E-02	0.0000E+00
4	48015319	0.1696E-02	-0.3860E-06	0.2273E-03	0.9126E-02	0.0000E+00

DATA FOR BUSHING VOLTAGE TRANSFORMER

DAY	NO. OF SAMPLES	VOLTAGE COEFFICIENT	TEMPERATURE COEFFICIENT (VOLTS/K)	CONSTANT (VOLTS)	STANDARD DEVIATION (VOLTS)	MEAN (VOLTS)
0	62157769	0.1603E-02	-0.3474E-05	0.1418E-01	0.1149E-01	0.0000E+00
1	62156017	0.1639E-02	-0.1030E-05	0.1494E-02	0.1147E-01	0.0000E+00
2	62136817	0.1631E-02	-0.5904E-06	-0.9516E-03	0.1132E-01	0.0000E+00
3	62103013	0.1627E-02	-0.5742E-06	-0.1008E-02	0.1141E-01	0.0000E+00
4	48015319	0.1609E-02	-0.5808E-06	-0.1021E-02	0.1152E-01	0.0000E+00

DATA FOR RELAYING CT

DAY	NO. OF SAMPLES	CURRENT COEFFICIENT	TEMPERATURE COEFFICIENT (AMP/K)	CONSTANT (AMP)	STANDARD DEVIATION (AMP)	MEAN (AMP)
0	62157769	0.7794E+00	-0.6328E-05	0.3818E-01	0.1125E-01	0.0000E+00
1	62156017	0.7790E+00	-0.1671E-05	0.1420E-01	0.1125E-01	0.0000E+00
2	62136817	0.7799E+00	-0.2790E-05	0.1980E-01	0.1130E-01	0.0000E+00
3	62103013	0.7805E+00	-0.1477E-05	0.1294E-01	0.1127E-01	0.0000E+00
4	48015319	0.7793E+00	-0.1116E-04	0.6229E-01	0.1130E-01	0.0000E+00

Figure 4. Calibration of the signal conditioner unit

Chapter 5. Hardware

5.1 Introduction

This chapter briefly describes various hardware components used in this project. It explains the interconnection between major components and also the working of the major components to some extent.

5.2 Measurement unit

Figure 5 shows the schematic diagram of the measurement unit installed in the field.

The signal conditioner gets its inputs from the field. It provides isolation for these signals. It also amplifies or steps down the signals to give the required levels of voltages to the A/D converter. The signal conditioner also provides filtering and sample-and-hold circuits.

The field computer has a Motorola CPU, and a Data Translation A/D board. The A/D board converts the analog signals to digital data and feeds it to the CPU. The CPU has the actual program which processes the data and sends it to any remote location (Virginia Tech Power Lab), over a telephone line. The communication is made possible by two modems, one connected at each end of the telephone line.

At the remote location is the host computer. The computer can be any IBM PC compatible model. The host computer collects the data from the field computer on demand. It can also diagnose the working of the computer to some extent.

5.3 Signal conditioner unit

The signal conditioner unit was provided by the American Electric Power Service Corporation. Some modifications were done in it to suit this project. The back plate of the signal conditioner unit appears as shown in the figure 6.

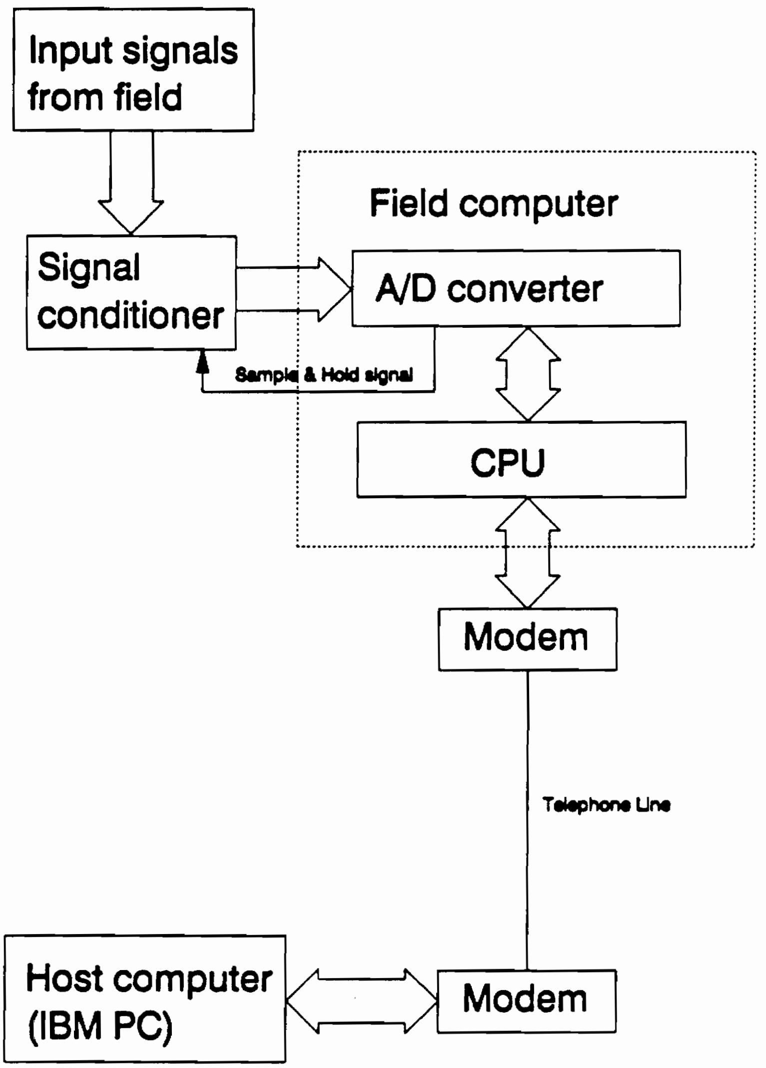

Figure 5. Schematic diagram of the measurement unit

5.3.1 Input/Output connections of the signal conditioner unit

As shown in the figure 6, the inputs from CTs and CVTs should be connected to the barrier strip. The input to the signal conditioner unit coming from the field has two currents and three voltages and a temperature sensor. The currents should have a maximum range of 5 Amperes (r.m.s) in the relaying CT, and 3.65 Amperes (r.m.s) in the metering C.T. The voltages should have a maximum range of 67 Volts (r.m.s).

The CPU sends sample-and-hold signals to the unit through a ribbon cable. This is connected to a DB-25 connector on the backplate.

The output voltages from each channel are taken to the DB-25 connector through a ribbon cable.

5.3.2 Working of the signal conditioner

Figure 7 and 8 show the schematic diagrams of the voltage channels and the current channels inside the signal conditioner unit. The voltages are scaled down by three step down voltage transformers. The currents are scaled down by two auxiliary current transformers. A shunt of 50 Ω resistance is connected across the secondary winding of each step down current transformer. The voltage across the

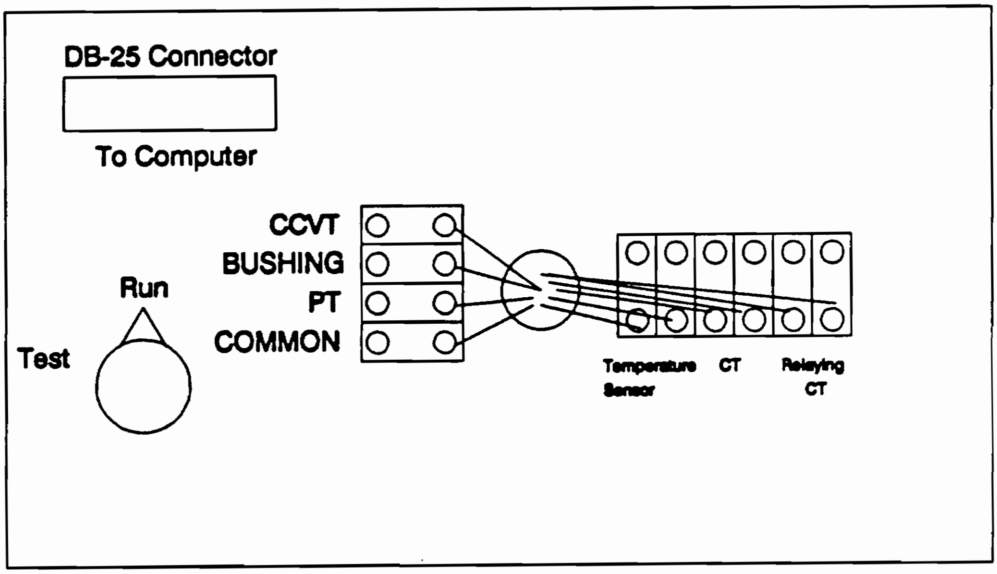

Figure 6. The backplate of the signal conditioner unit

shunt is taken as the current measurement. Both current and voltage channels are protected by EMI filters. The current channels are protected further by current limiting resistances. The voltage transformers and the EMI filters are mounted on the same PCB, while current transformers are mounted on the chassis of the signal conditioner.

The signal conditioner unit has two boards, viz the isolation board and the filter board. The first PCB (isolation board) carries 3 voltage channels, two current channels and one temperature channel.

The second PCB (filter board) receives 6 input signals from the first PCB. The signals are amplified to the desired levels using isolation amplifiers. Then the signals are filtered by a 2 stage RC low pass filter, with cutoff frequency of 300 Hz. The filter is required to remove aliasing effect of the sampling frequency, which is 720 Hz.

The filtered signals are passed to isolating amplifiers and then to "Sample-and-Hold" circuits. The sample-and-hold signals from the CPU are connected to these channels separately, i.e each channel has its own sample-and-hold signal.

As mentioned before, a temperature sensor is required. One possibility was to build the sensor using a varistor. But since the sensor has to be kept in the substation yard, it would have been affected by noise. Also it is very difficult to design the sensor using a varistor, to obtain calibrated temperature readings. Another possibility was to get temperature reading from the substation thermometer. The thermometer should provide a voltage directly proportional to the temperature. This would be brought to the signal conditioner unit and amplified if necessary to get the required range. The minimum temperature should produce a voltage higher than -10 volts and the maximum temperature should produce a voltage less than $+10$ volts.

The final choice was made by using a current sourcing device. As shown in the figure 9 temperature sensor provides current proportional to temperature. The relation is 1 milliamp per degree Kelvin. A shunt is connected across this current to give a voltage. This output voltage is amplified further on the signal conditioner filter board. The temperature sensor is scaled so that it gives 20.26 milivolts per degree Kelvin. This means that the A/D board sees the temperature as 4.15 A/D count per degree Kelvin. The circuit for temperature sensor is mounted on the filter board.

5.4 The field computer

The field computer appears as shown in the figure 10.

On the backplate, there are 3 "DB-25" connectors. Two of them are serial ports and one is a parallel port.

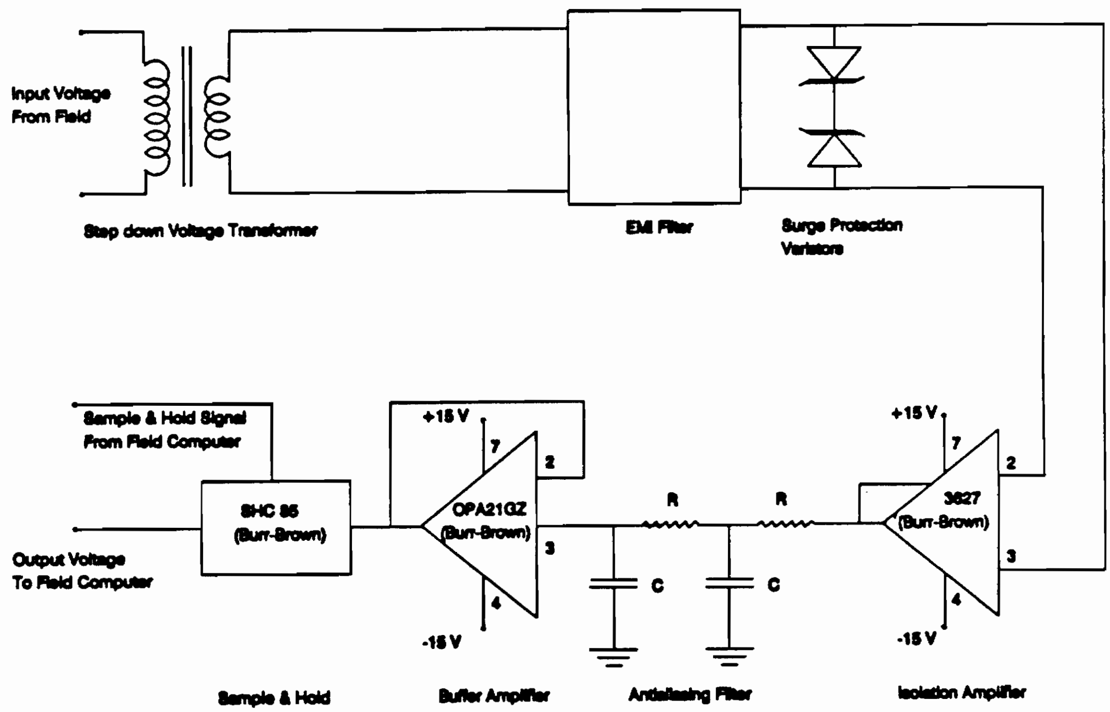

Figure 7. Schematic diagram of a voltage channel

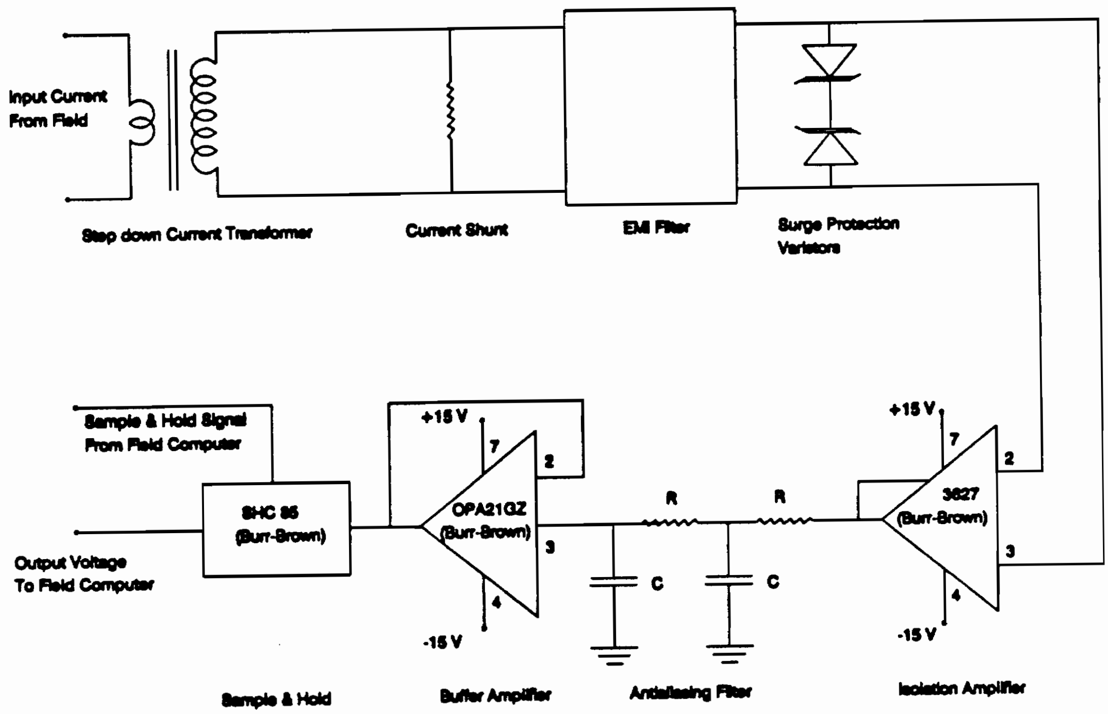

Figure 8. Schematic diagram of a current channel

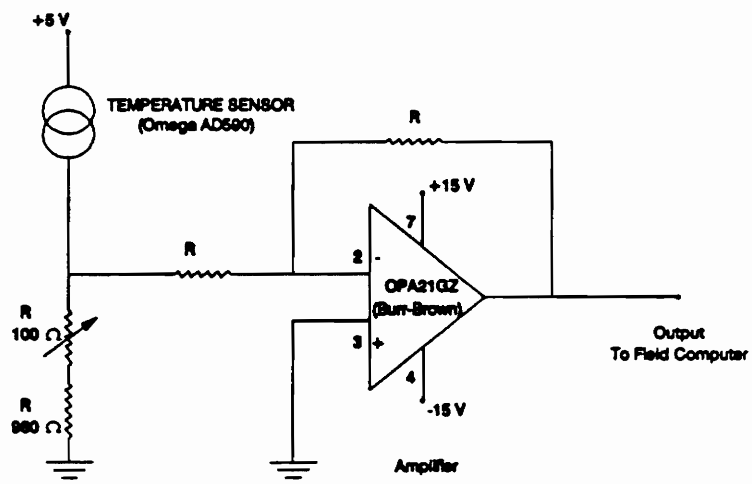

Figure 9. Schematic diagram of temperature sensor

The connector marked "Terminal" is a USART RS485 serial port [5] and can be connected to a local terminal, e.g Digital VT200, while loading the program or while debugging the program. The memory space on the CPU board can be accessed by this serial port, using a local terminal.

The connector marked "Modem" is a general purpose RS-232 serial port. This should be connected to the modem (Hayes compatible) [17] to communicate with the host computer. The same serial port is used in the laboratory to download the assembled program from MicroVAX (in laboratory) to Motorola 68020 [4].

The connector marked "Signal Conditioner" is a parallel port and it should be connected to the signal conditioner unit.

Inside the computer there are two boards. One is a Motorola 68020 CPU board in the lower-most slot. The second board is a Data Translation DT-1402 A/D board. The ribbon cable coming from the signal conditioner is connected to the two parallel ports on the A/D converter. From one parallel port the CPU sends the "Sample-and-Hold" signals. The second port provides the input channels for the analog signals. The modem is connected to the CPU RS-232 port on the CPU board. The two boards communicate with each other through VME the bus.

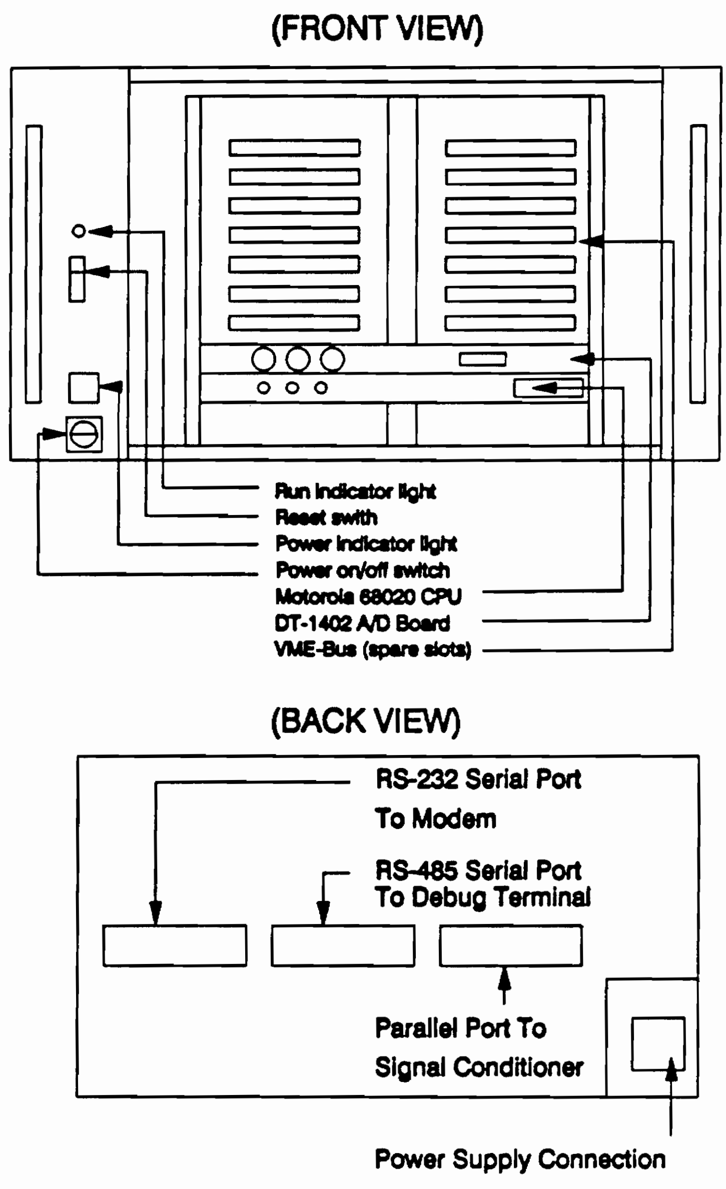

Figure 10. The field computer.

5.5 Modems

Hayes Smartmodem 1200 are used for the communication [17]. As shown in figure 11, the telephone line is connected to the slot named "To Line". A telephone may be connected to the slot named "Telephone". However, the voice telephone cannot be used if the modem is on. There is a RS-232 serial port on the back of the modem. A four wire cable should be connected from the modem to the computer in the measuring unit. This wire connection is shown in the figure 11. Whenever the host computer calls the measuring unit, the modem must be on.

At the host end one more modem is used to connect the host to the telephone line. It is also connected in a similar way, except that the 2 and 3 wires in the four wire cable are not crossed over. This is also shown in figure 11. This connection is valid only for COM 1 port of IBM PC or compatible [10].

These modems are programmed by setting the hardware switches to send and receive data at 1200 baud rate using one stop bit, no parity, and 8 bit character length. Additional modem configuration and handshaking is handled through software by each computer at their respective ends.

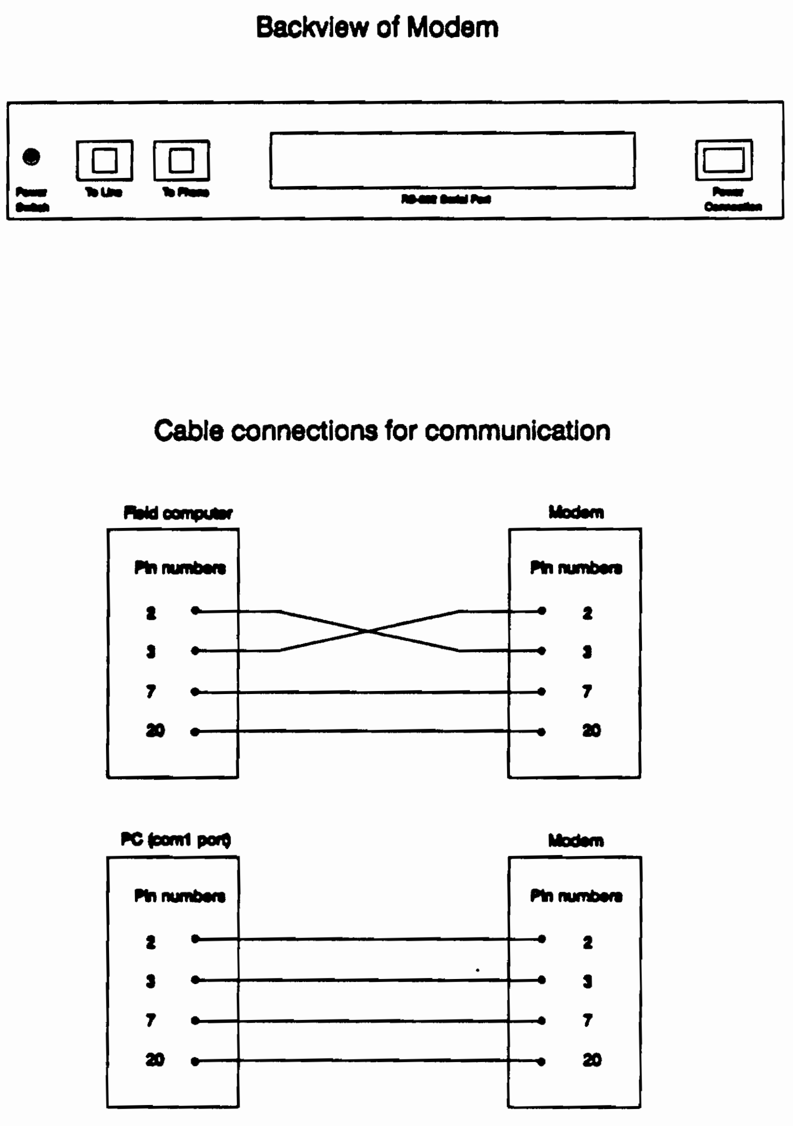

Figure 11. Modem connections.

Chapter 6. Analysis and Results

6.1 Introduction

The data collected for 121 days is analyzed in this chapter. Each coefficient for each transducer is plotted against time, maximum temperature, maximum voltage peak or maximum current peak to find obvious trends in the behavior of the data. The results are discussed in the following sections.

Also in the last section of this chapter, the error coefficients computed for a table of raw samples collected from the field is presented.

6.2 Data on a typical day

Figure 12 shows a sample of data collected on a particular day. The first line shows the day on which the data was collected. The second and third lines show the maximum and minimum temperature recorded during the day. The temperature recording is equal to 4.15 times the absolute temperature measured in Kelvin. This particular scale was chosen to get maximum dynamic range within the hardware for the temperature sensor. The next lines show the amount of third harmonic content in each channel averaged over that day. The lines below that show the various coefficients of the parameters in the error model for CCVT,Bushing Voltage Transformer and the relaying CT. They are divided into three blocks as described below. The first line of the first block shows the number of samples taken for the first coefficient **a** of the error model. This coefficient is the voltage coefficient, and does not have any units. The next line is the coefficient of temperature. It is measured in the A/D converter count per degree Kelvin. It has to be properly scaled to give temperature coefficients in volts per Fahrenheit. The next line is the d.c offset which is given in units of A/D converter count (+ 10 V is equal to 2047 of A/D count). The line below that is the standard deviation of the noise which is again measured in the A/D converter count. The last line is the mean of the random noise which was always found to be zero. The next two blocks show the coefficients for the Bushing Voltage Transformer and the relaying CT. The coefficients of the error model parameters are measured in the same units as described above for CCVT.

6.2.1 Scaling of data

The numbers obtained from the measuring unit in the field have to be properly scaled to give meaningful data. This scaling is explained in this section.

The temperature readings have to be divided by 4.15 to convert it into degrees Kelvin. To convert it into Celsius we have to subtract 273.15 from the Kelvin measurement. To convert the measurement further into Fahrenheit multiply the Celsius measurement by 1.8 and add 32.

The voltage and current peaks recorded are given in A/D converter count. The A/D converter is a signed 11 bit long word, and its dynamic range is from +10 V to -10 V, which means one bit of A/D converter represents 4.883 milivolts. Therefore the voltage and current peaks have to be multiplied by 4.883 milivolts to convert them into volts.

The temperature coefficient " b " has to be multiplied by 4.15 to convert it into A/D counts per Kelvin. To convert it into volts per Kelvin it has to be multiplied further by 4.883 milivolts.

```
DAY  :  50
MAXIMUM TEMPERATURE RECORDED : 1172 F
MINIMUM TEMPERATURE RECORDED : 1112 F

MAXIMUM AND MINIMUM PEAKS RECORDED :
   METERING          CCVT          BUSHING          METERING          RELAYING
     P.T                             P.T              C.T               C.T
     1988            2010            1936             1348              1350
     1860            1880            1814             426               424

AVERAGE PEAKS OF THIRD HARMONIC RECORDED :
   METERING          CCVT          BUSHING          METERING          RELAYING
     P.T                             P.T              C.T               C.T
     22              15              10               3                 4

COEFFICIENTS OF ERROR MODEL FOR CCVT :
NO OF SAMPLES : 48945600
CURRENT COEFFICIENT :  1.3610330913981300  E-002
TEMPERATURE COEFFICIENT : -1.1248930610067000  E-003
CONSTANT COEFFICIENT : -5.7260569112126500  E-001
STANDARD DEVIATION OF NOISE :  2.2873440670656055  E 000
MEAN OF NOISE :  0.0000000000000000  E 000

COEFFICIENTS OF ERROR MODEL FOR BUSHING VT :
NO OF SAMPLES : 48945600
CURRENT COEFFICIENT : -1.7393314482225200  E-002
TEMPERATURE COEFFICIENT : -2.7902699955364000  E-003
CONSTANT COEFFICIENT :  9.2903453740067340  E-001
STANDARD DEVIATION OF NOISE :  2.1770193470355511  E 000
MEAN OF NOISE :  0.0000000000000000  E-016

COEFFICIENTS OF ERROR MODEL FOR RELAYING CT :
NO OF SAMPLES : 48945600
CURRENT COEFFICIENT : -4.0853774113320000  E-004
TEMPERATURE COEFFICIENT : -1.6179532638182000  E-003
CONSTANT COEFFICIENT :  1.3401017854627132  E 000
STANDARD DEVIATION OF NOISE :  2.1696894187665409  E 000
MEAN OF NOISE : -0.0000000000000000  E-016
```

Figure 12. Data collected on a typical day

The d.c offset " c " and variance " σ " are measured in A/D count, therefore it should be multiplied by 4.883 milivolts to convert them into volts.

The data shown in figure 12 is scaled as explained in this section and shown again in figure 13 for comparison.

6.4 Analysis of the field data

6.4.1 Voltage coefficient and current coefficient

Figures 14 through 37 show the behavior of the coefficient for the first parameter, spread over 121 days. The coefficient is also compared to the maximum temperature recorded during the day.

Looking at the first coefficient plotted against time (in days) we do not find any particular trend. This means that the first coefficient does not show effects of aging over this time span. However the coefficient shows variation in magnitude if we plot it against the temperature measured during the day. Figure 14 shows the voltage coefficient for the CCVT plotted against the maximum temperature recorded during the day (in Fahrenheit). The coefficient is increasing with increase in temperature. The solid line is the least squared mean of the data.

DAY : 50
MAXIMUM TEMPERATURE RECORDED : 48 F
MINIMUM TEMPERATURE RECORDED : 22 F

MAXIMUM AND MINIMUM PEAKS RECORDED :

METERING P.T	CCVT	BUSHING P.T	METERING C.T	RELAYING C.T
0.9707E+01 V	0.9814E+01 V	0.9453E+01 V	0.2781E+01 A	0.2785E+01 A
0.9082E+01 V	0.9180E+01 V	0.8857E+01 V	0.8789E+00 A	0.8748E+00 A

AVERAGE PEAKS OF THIRD HARMONIC RECORDED :

METERING P.T	CCVT	BUSHING P.T	METERING C.T	RELAYING C.T
0.1074E+00 V	0.7324E-01	0.4883E-01 V	0.6189E-02 A	0.8253E-02 A

COEFFICIENTS OF ERROR MODEL FOR CCVT :
NO OF SAMPLES : 48945600
VOLTAGE COEFFICIENT : 0.1361E-01
TEMPERATURE COEFFICIENT : -0.1324E-05 VOLTS/K
CONSTANT COEFFICIENT : -0.2796E-02 VOLTS
STANDARD DEVIATION OF NOISE : 0.1117E-01 VOLTS
MEAN OF NOISE : 0.0000000000000000 E 000 VOLTS

COEFFICIENTS OF ERROR MODEL FOR BUSHING VT :
NO OF SAMPLES : 48945600
VOLTAGE COEFFICIENT : -0.1739E-01
TEMPERATURE COEFFICIENT : -0.3283E-05 VOLTS/K
CONSTANT COEFFICIENT : 0.4536E-02 VOLTS
STANDARD DEVIATION OF NOISE : 0.1063E-01 VOLTS
MEAN OF NOISE : 0.0000000000000000 E 000 VOLTS

COEFFICIENTS OF ERROR MODEL FOR RELAYING CT :
NO OF SAMPLES : 48945600
VOLTAGE COEFFICIENT : -0.4085E-03
TEMPERATURE COEFFICIENT : -0.1426E-05 AMPS/K
CONSTANT COEFFICIENT : 0.4903E-02 AMPS
STANDARD DEVIATION OF NOISE : 0.7938E-02 AMPS
MEAN OF NOISE : 0.0000000000000000 E 000 AMPS

Figure 13. Data collected on a typical day after scaling

The slope of this line is -0.1359E-04 per degree Fahrenheit, which is very small. Also the spread of the coefficients around the line is 0.4505E-02 which is large. This means that the temperature affects the voltage coefficient of the CCVT gradually and the changes are less consistent. In case of the Bushing Voltage Transformer, the voltage coefficient has an increasing trend with the increase in temperature. This is shown in figure 17. The slope of the least squared mean is 0.1235E-03 which is much higher than that for the CCVT. Also the spread of the coefficients around the mean is 0.1957E-01, which is very large. This shows that the Bushing Voltage Transformer is more susceptible to the temperature variation than the CCVT. However the changes are not very consistent. The relaying CT current coefficient tends to decrease with increase in temperature. This variation is larger than that of the CCVT as can be seen from figure 19. However the spread of the data around the mean is also very large suggesting that there is an effect of temperature variation on the current coefficient in the CT, but the variations are less consistent.

6.4.2 Temperature coefficient

The temperature coefficients for different transducers are plotted against time, as well as against the maximum temperature recorded during the day. These coefficients are very small (of the order of 10^{-5}). Therefore the instantaneous temperature does not contribute to the error in the transducers. The small numbers can be partly due to the noise inherent in the measuring unit, partly due to the round-off error in the A/D converter, and partly due to the stray noise.

6.4.3 Constant coefficient or d.c offset

The d.c offset for different transducers are plotted against time as well as against maximum temperature recorded during the day.

6.4.4 Standard deviation

The standard deviation of noise is plotted against time for each transducer. It is also given as percentage of maximum peak recorded during the day.

6.4.5 Mean of noise

The mean of noise was always found to be zero on all days for all channels. The mean must be zero since the d.c offset in the model is accounted by error parameter "c ". Therefore the mean is used only to check the validity of the calculations made.

6.4.6 Analysis of raw data

A table of 720 samples (for each channel), is obtained from the field. This is the raw data collected by the field computer, and measured in A/D converter count. The data is given in Appendix A. The error coefficients are calculated using a Fortran program simulating the same model as that used in the field computer. The results are presented in figure 38. The third harmonic content is removed from the data before calculating the error coefficients.

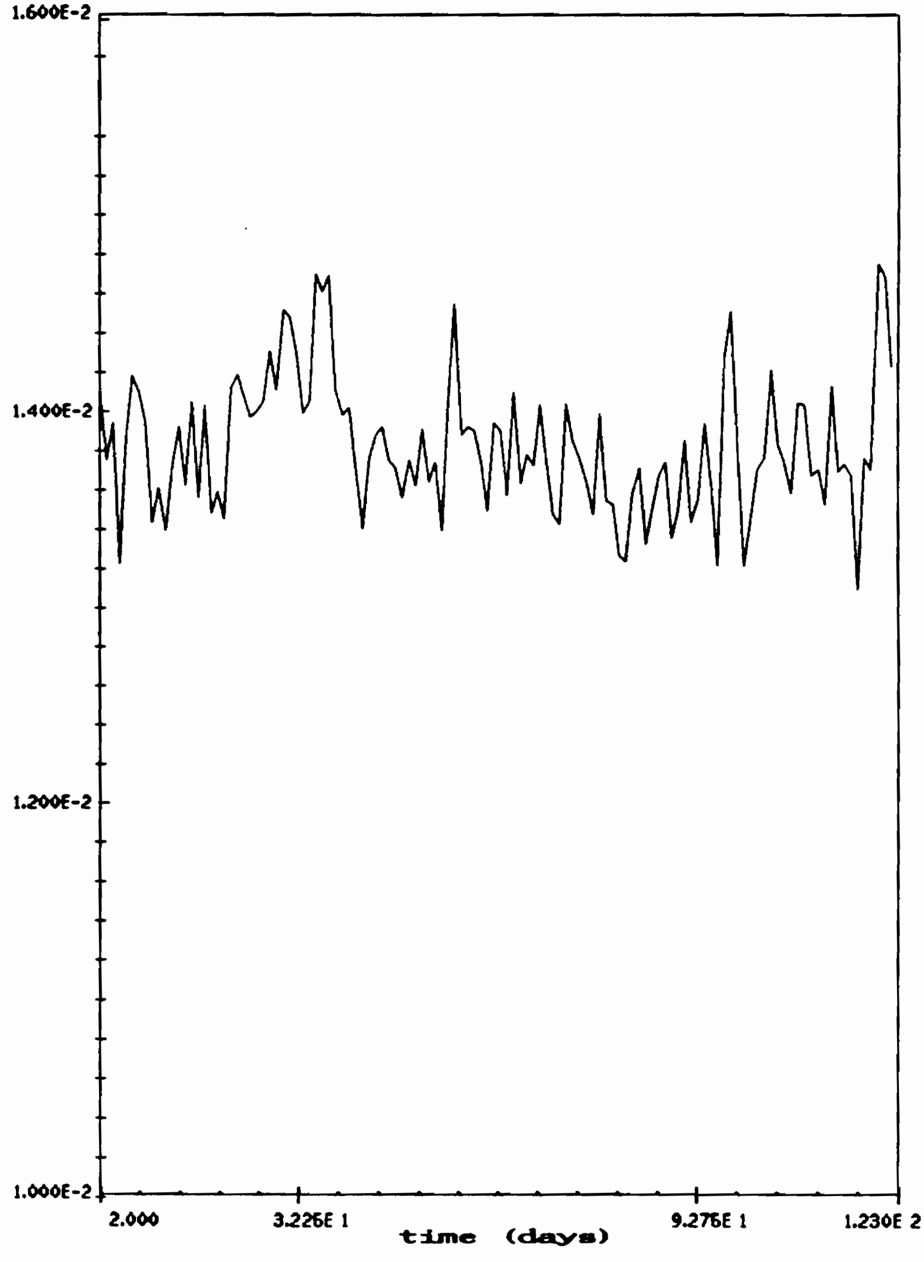

Figure 14. Plot of voltage coefficient v/s time for CCVT

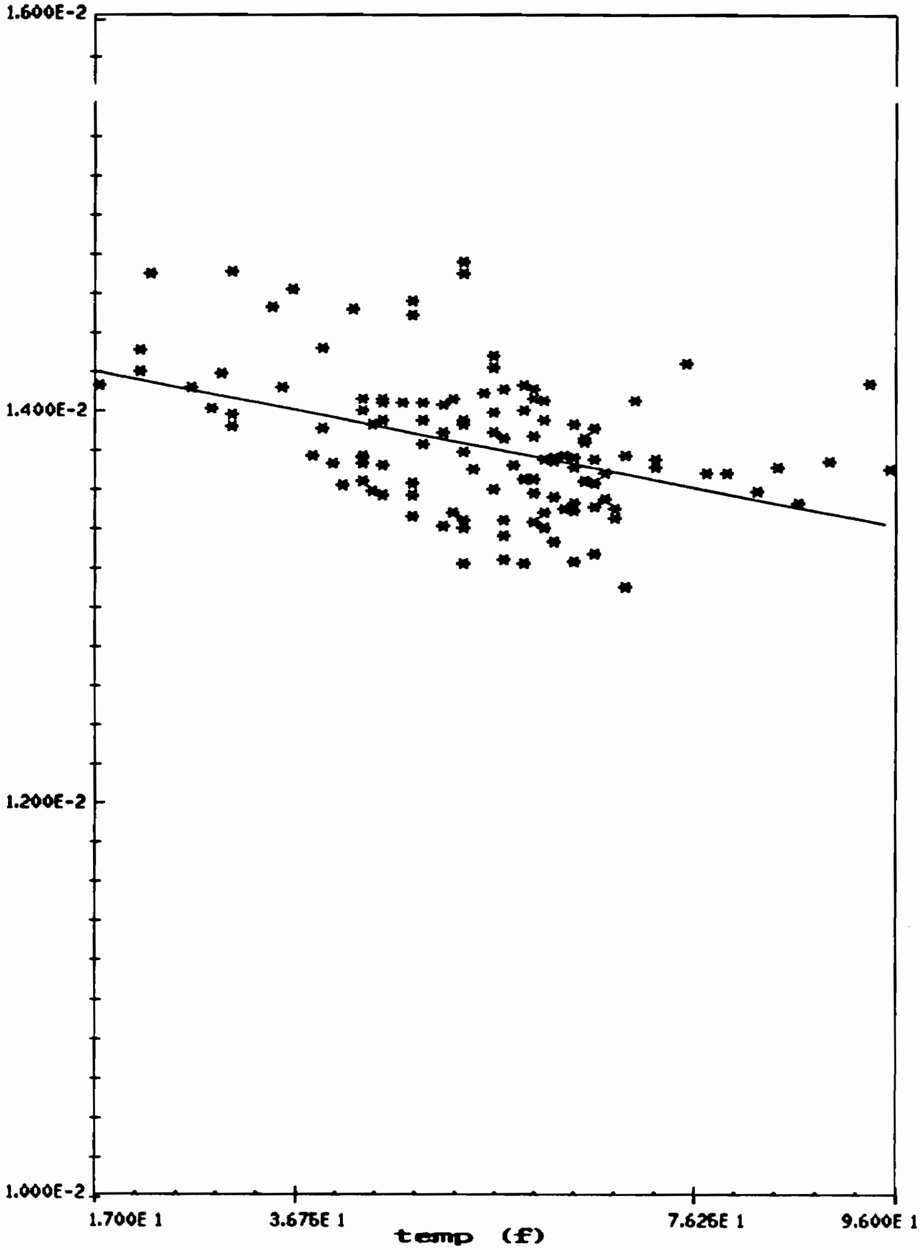

Figure 15. Plot of voltage coefficient v/s temperature for CCVT

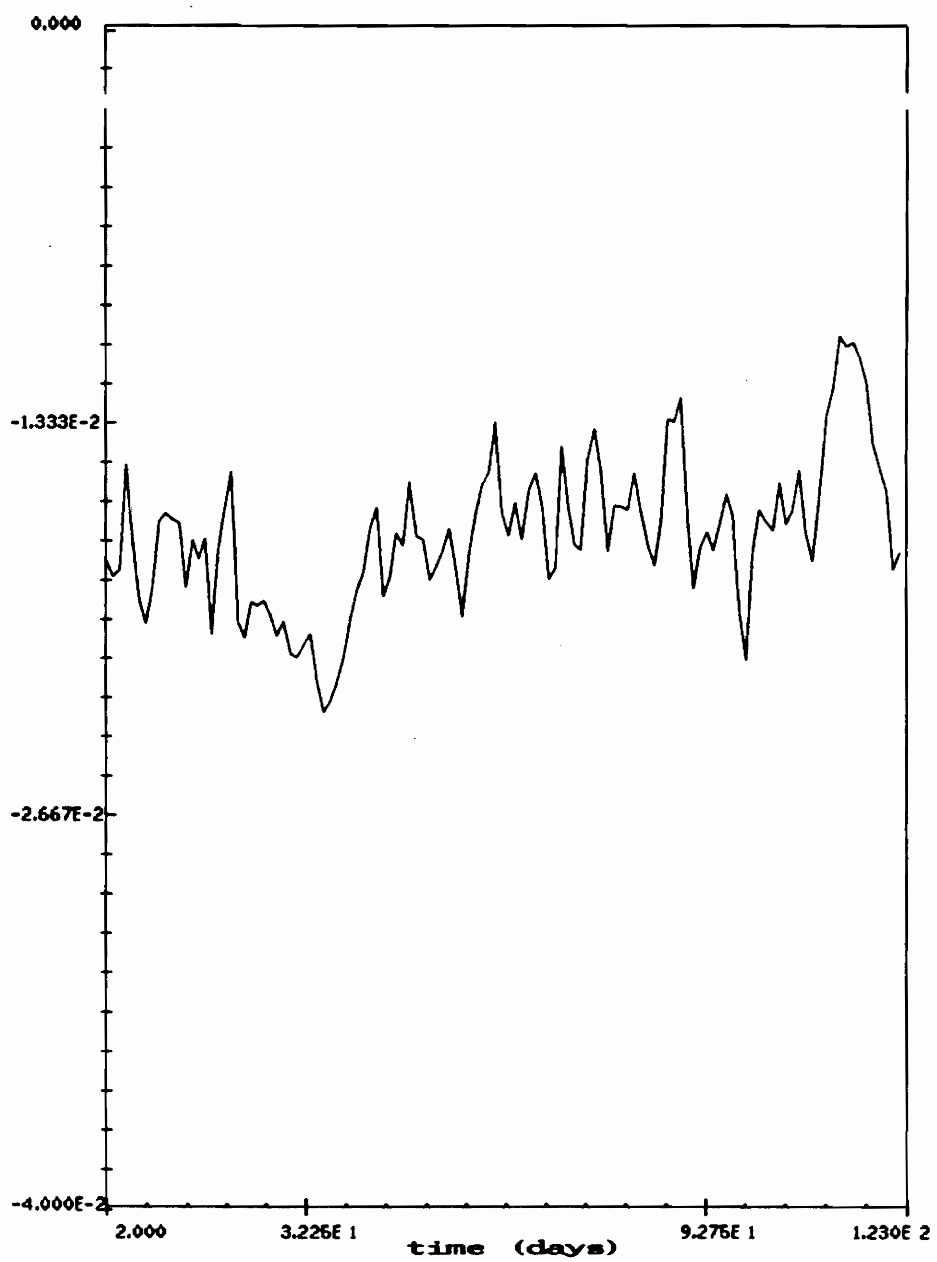

Figure 16. Plot of voltage coefficient v/s time for Bushing VT

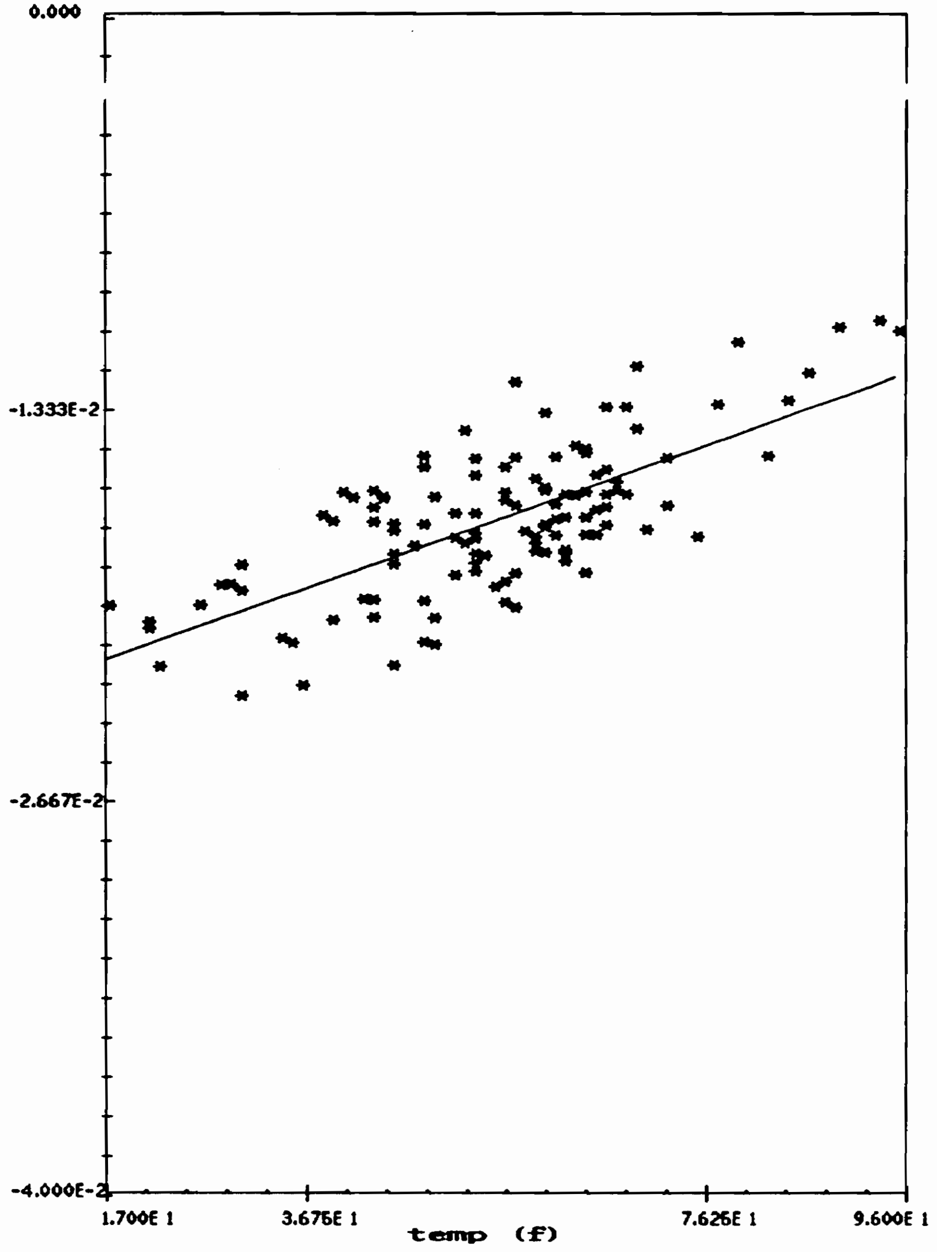

Figure 17. Plot of voltage coefficient v/s temperature for Bushing VT

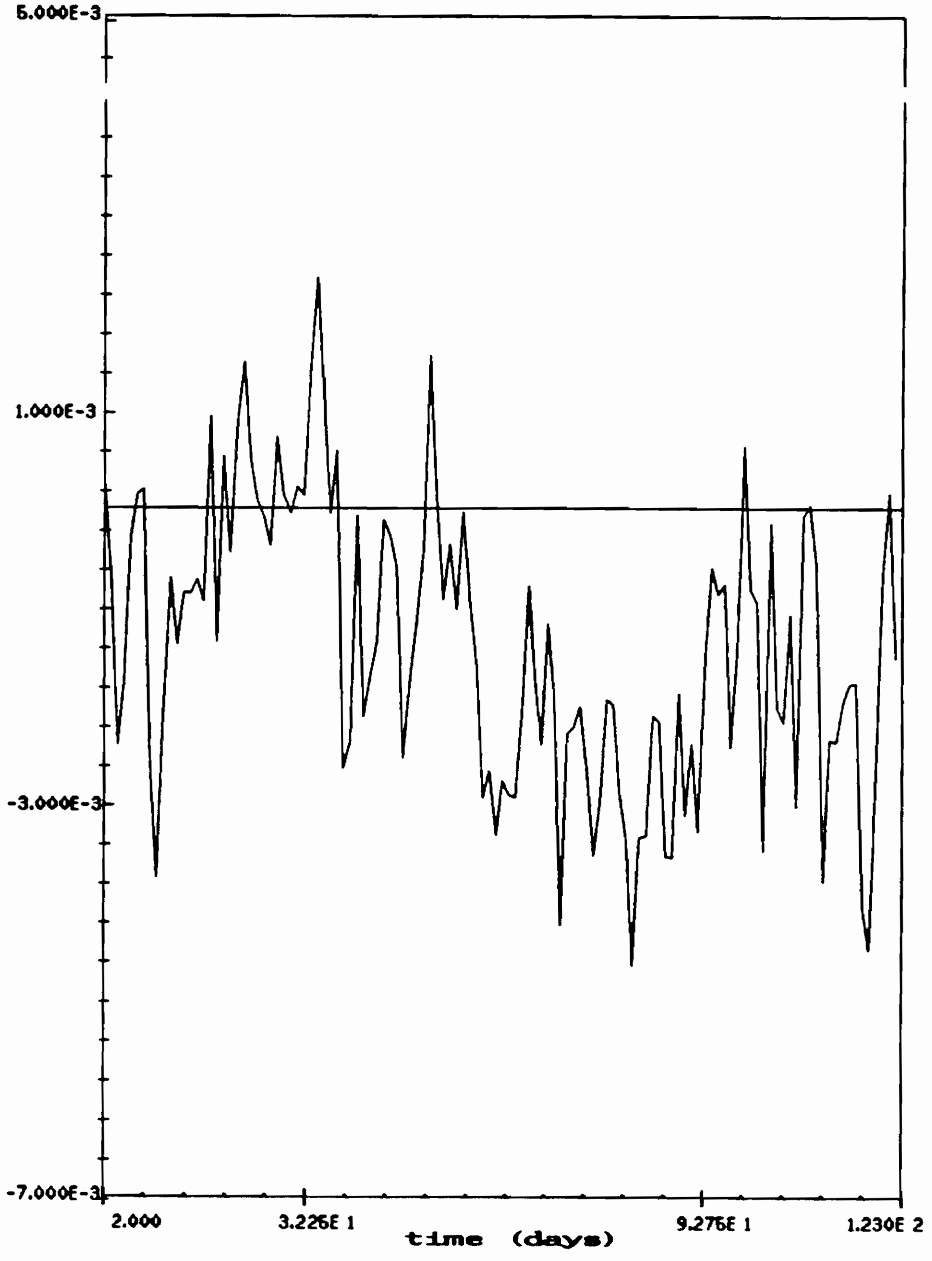

Figure 18. Plot of current coefficient v/s time for Relaying CT

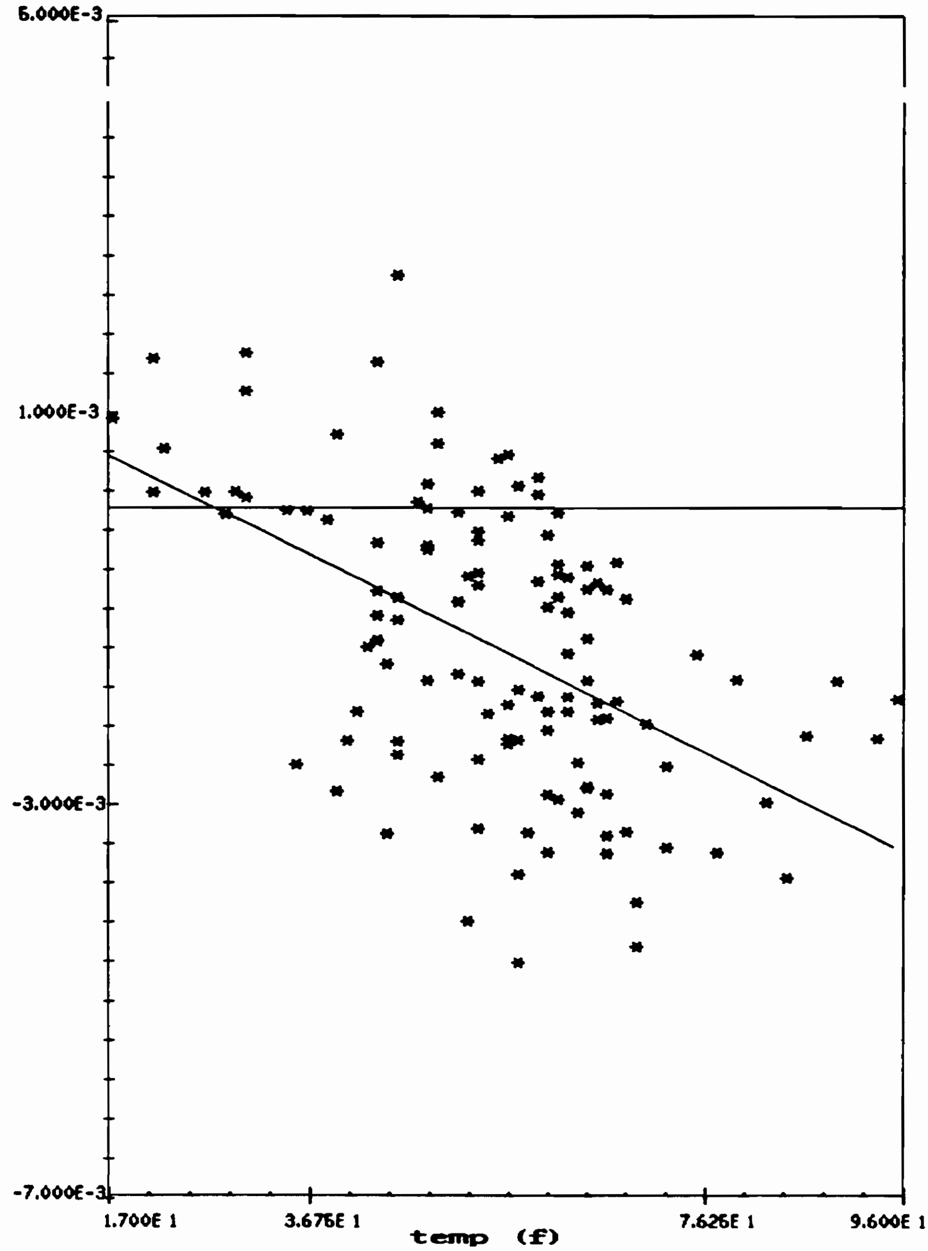

Figure 19. Plot of current coefficient v/s temperature for Relaying CT

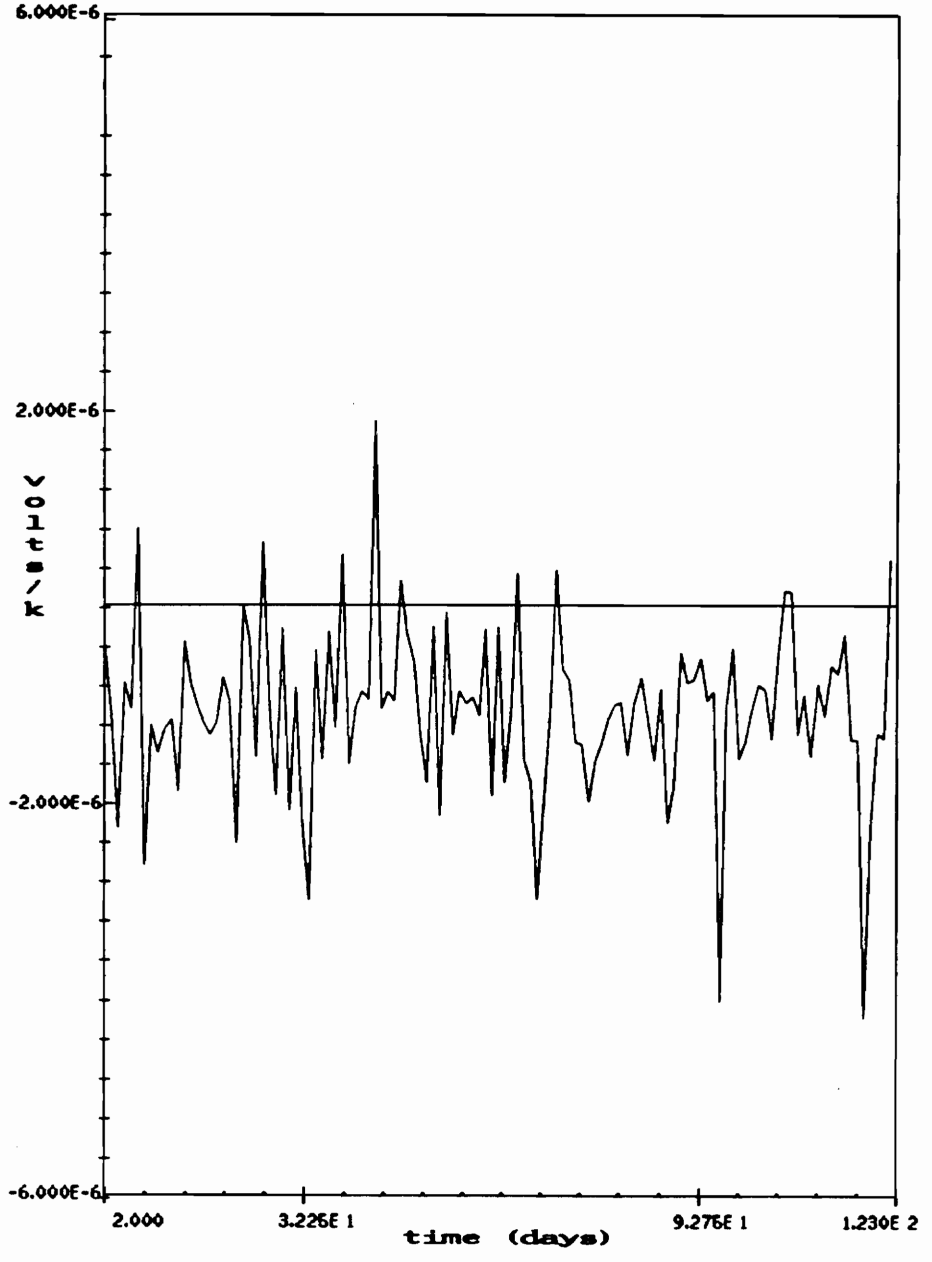

Figure 20. Plot of temperature coefficient v/s time for CCVT

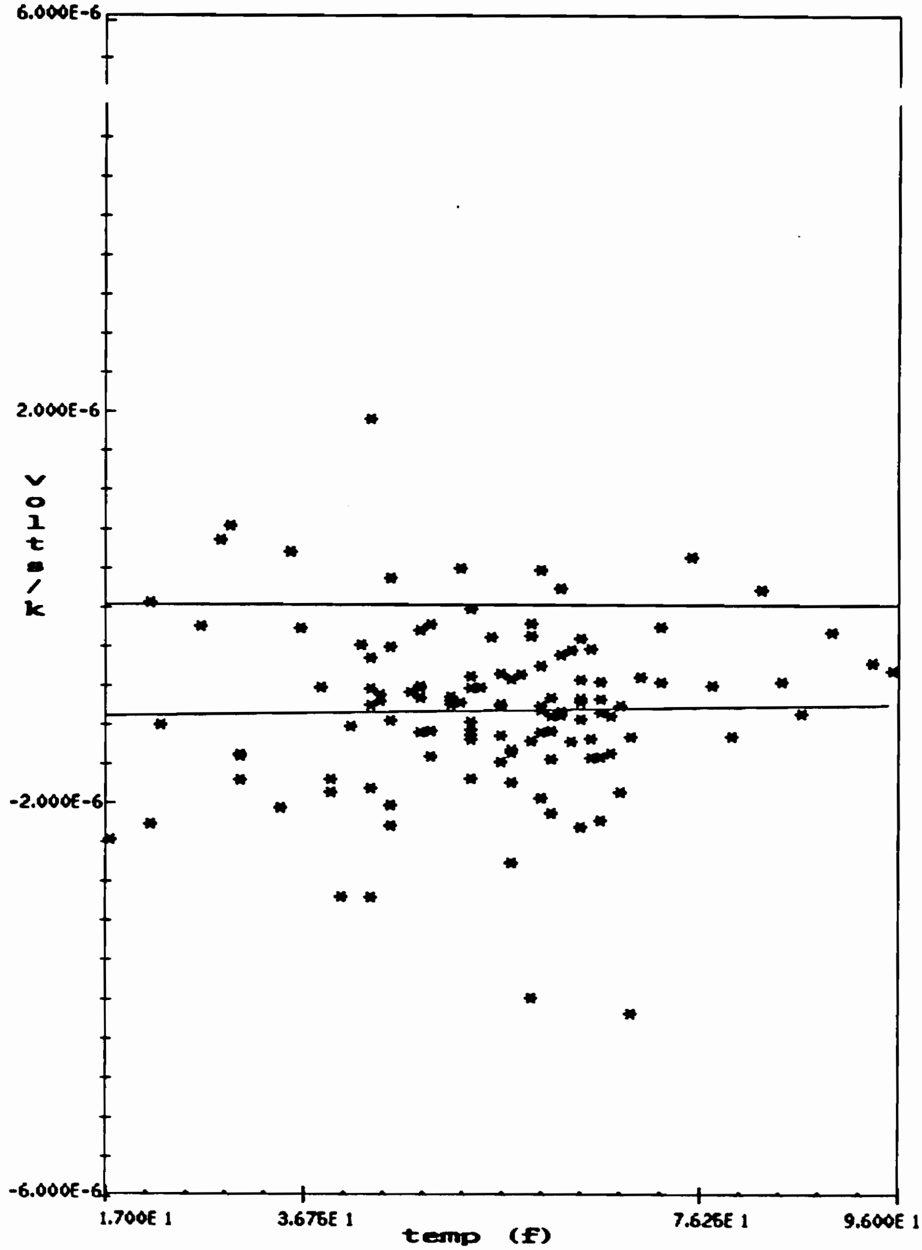

Figure 21. Plot of temperature coefficient v/s temperature for CCVT

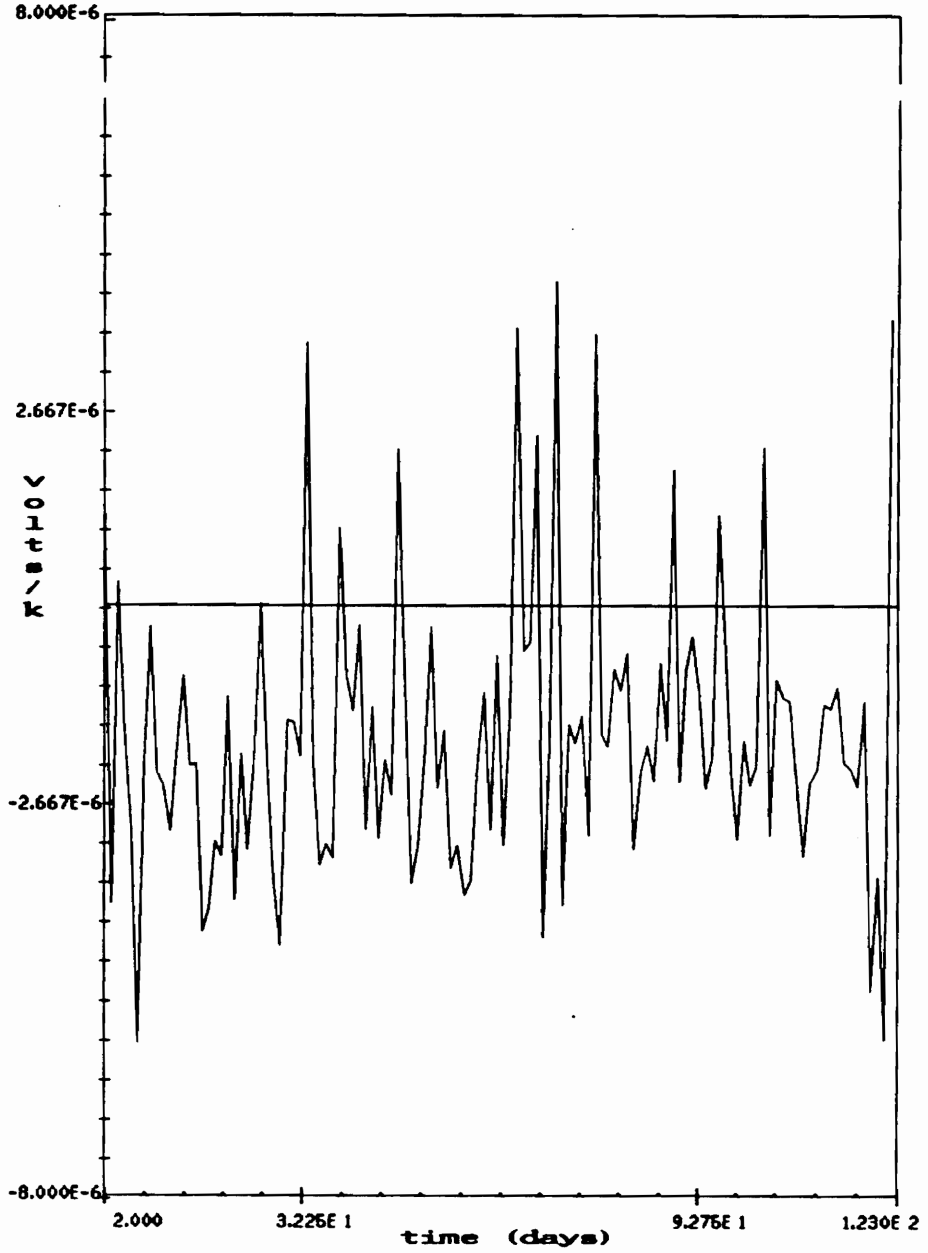

Figure 22. Plot of temperature coefficient v/s time for Bushing VT

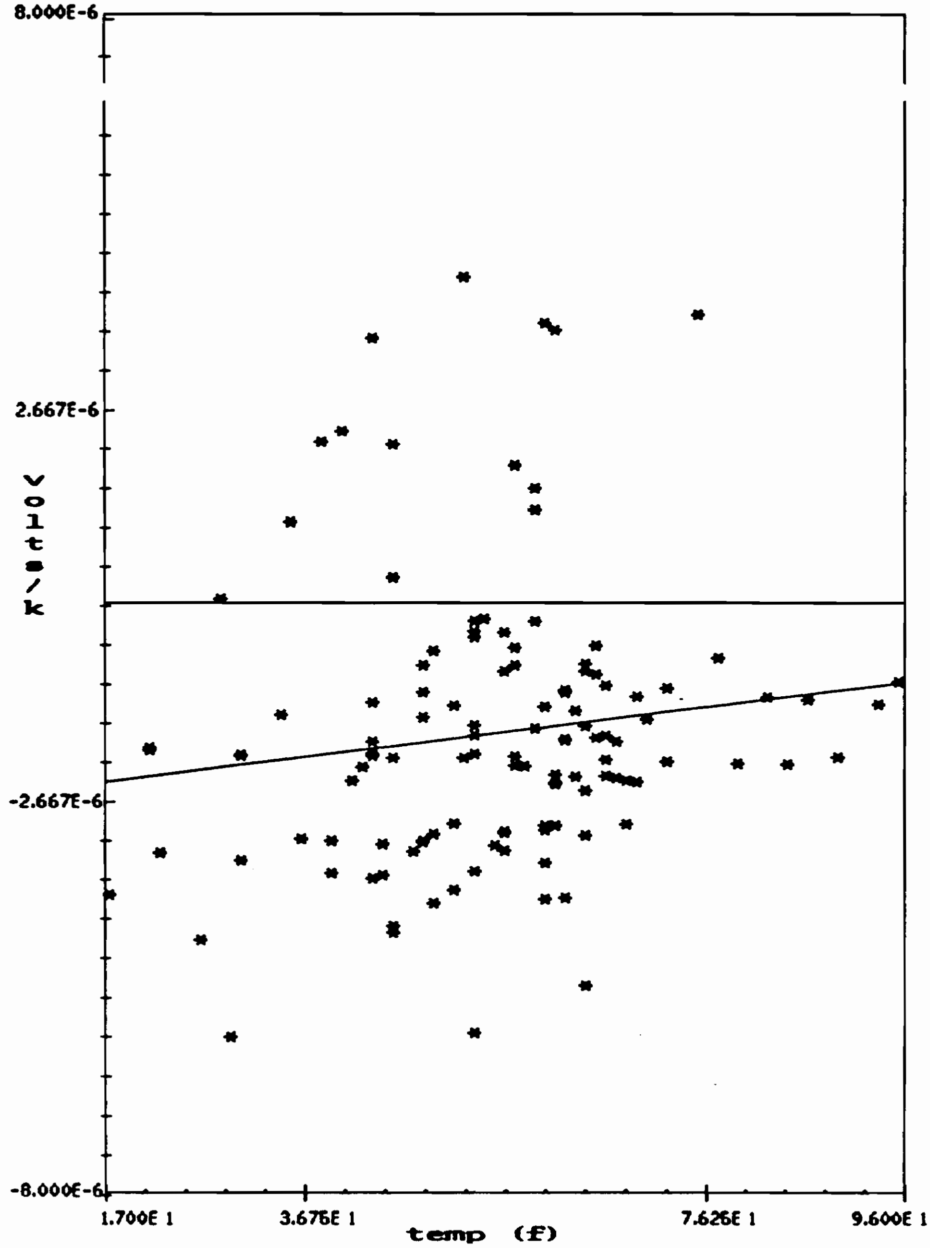

Figure 23. Plot of temperature coefficient v/s temperature for Bushing VT

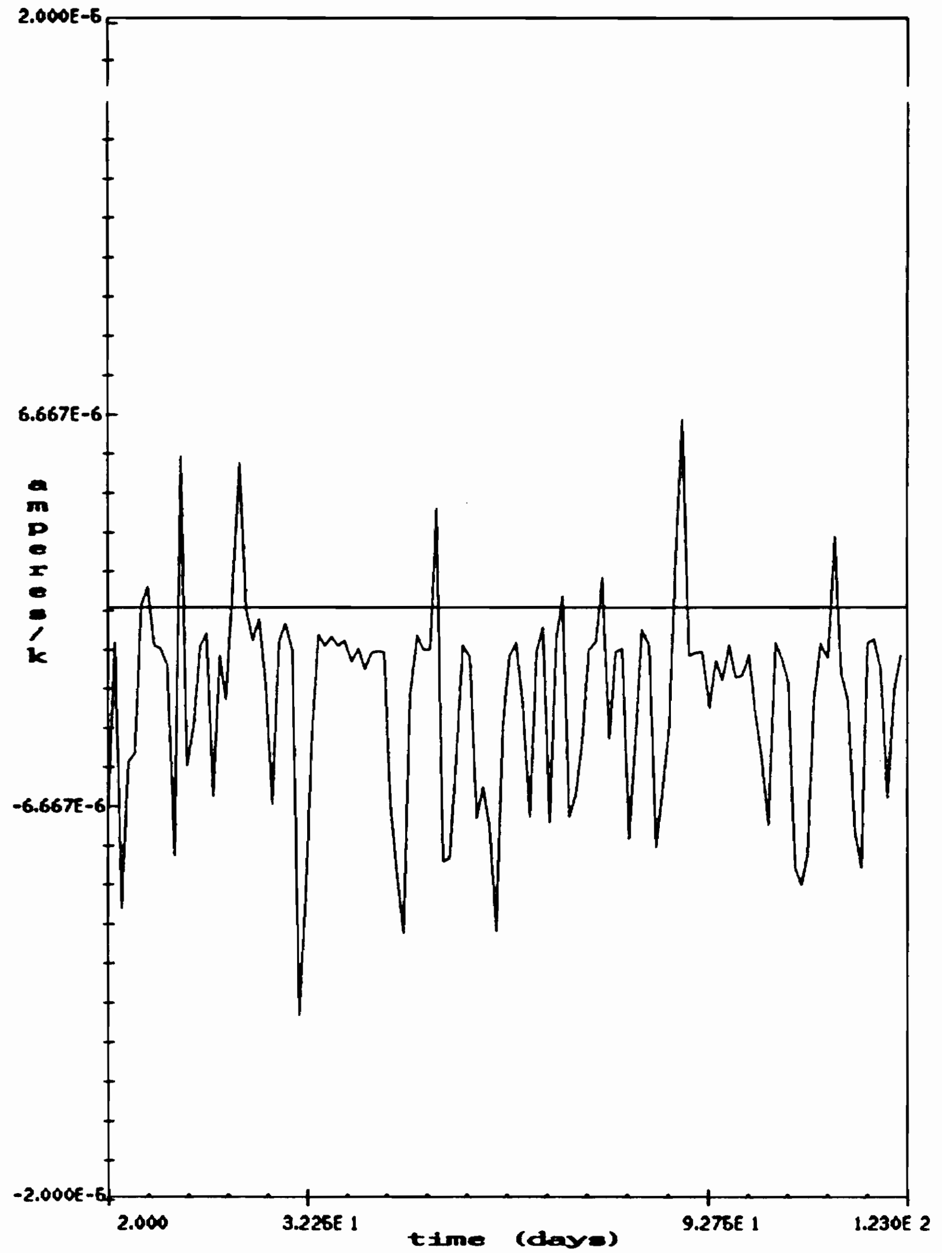

Figure 24. Plot of temperature coefficient v/s time for Relaying CT

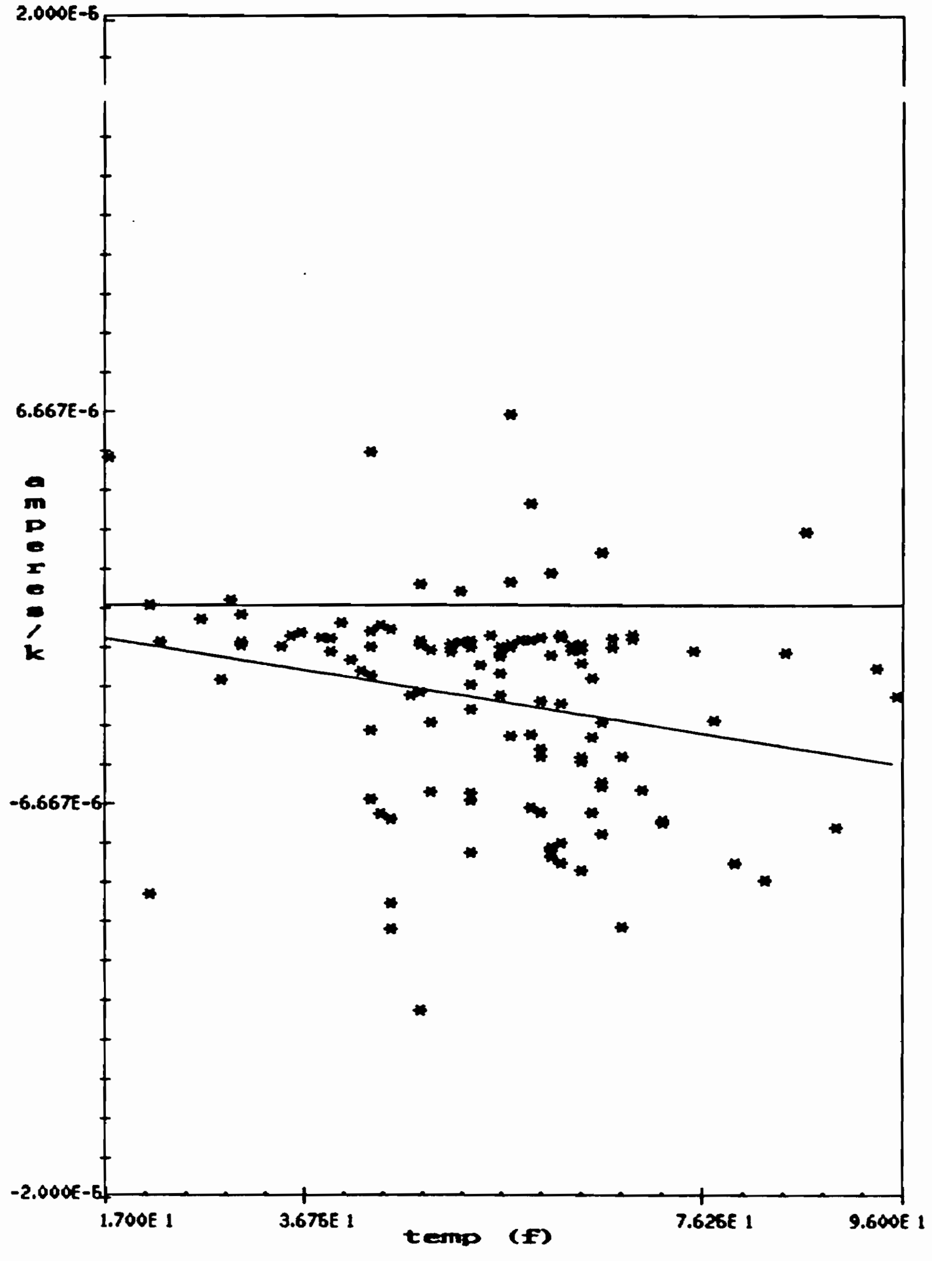

Figure 25. Plot of temperature coefficient v/s temperature for Relaying CT

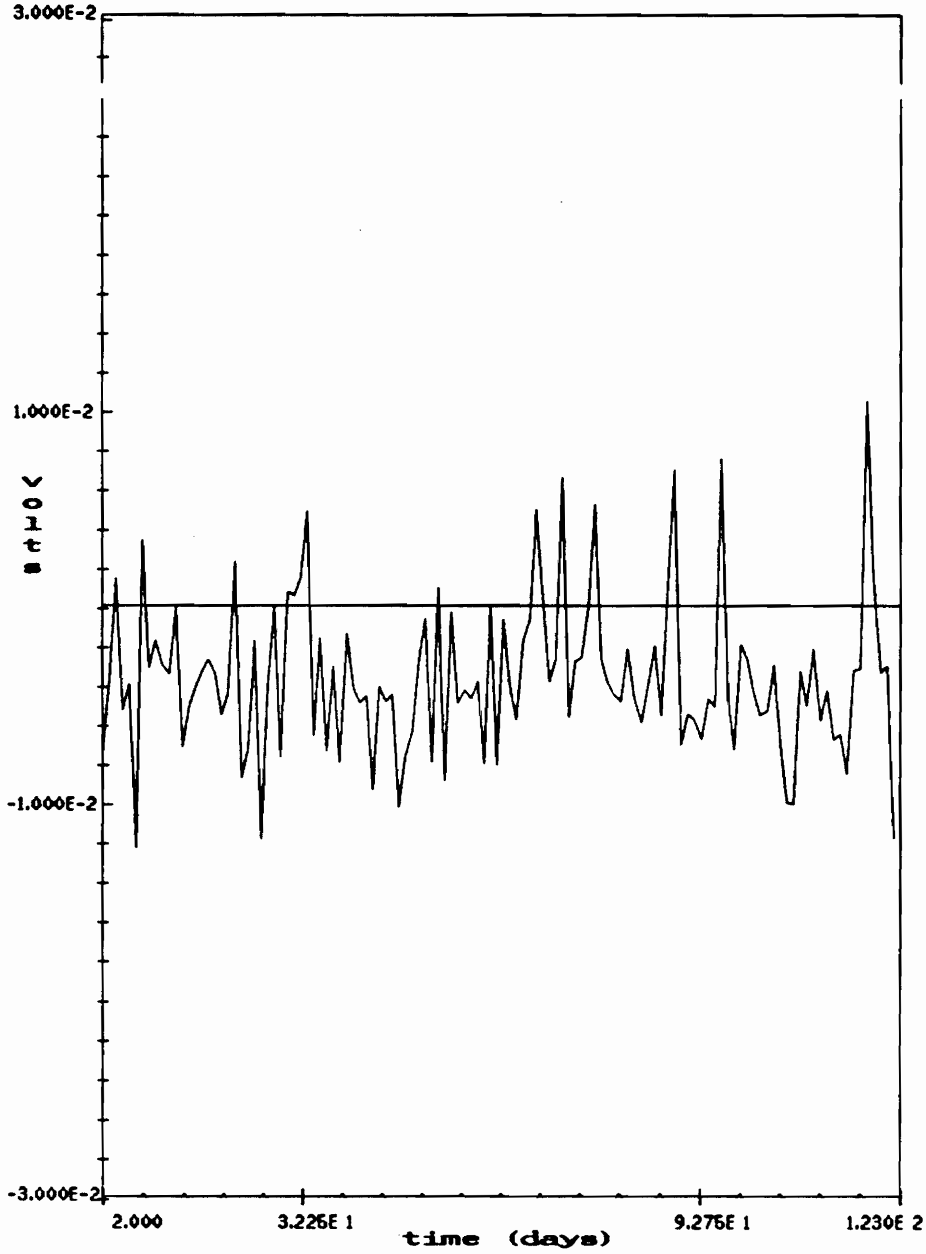

Figure 26. Plot of constant coefficient v/s time for CCVT

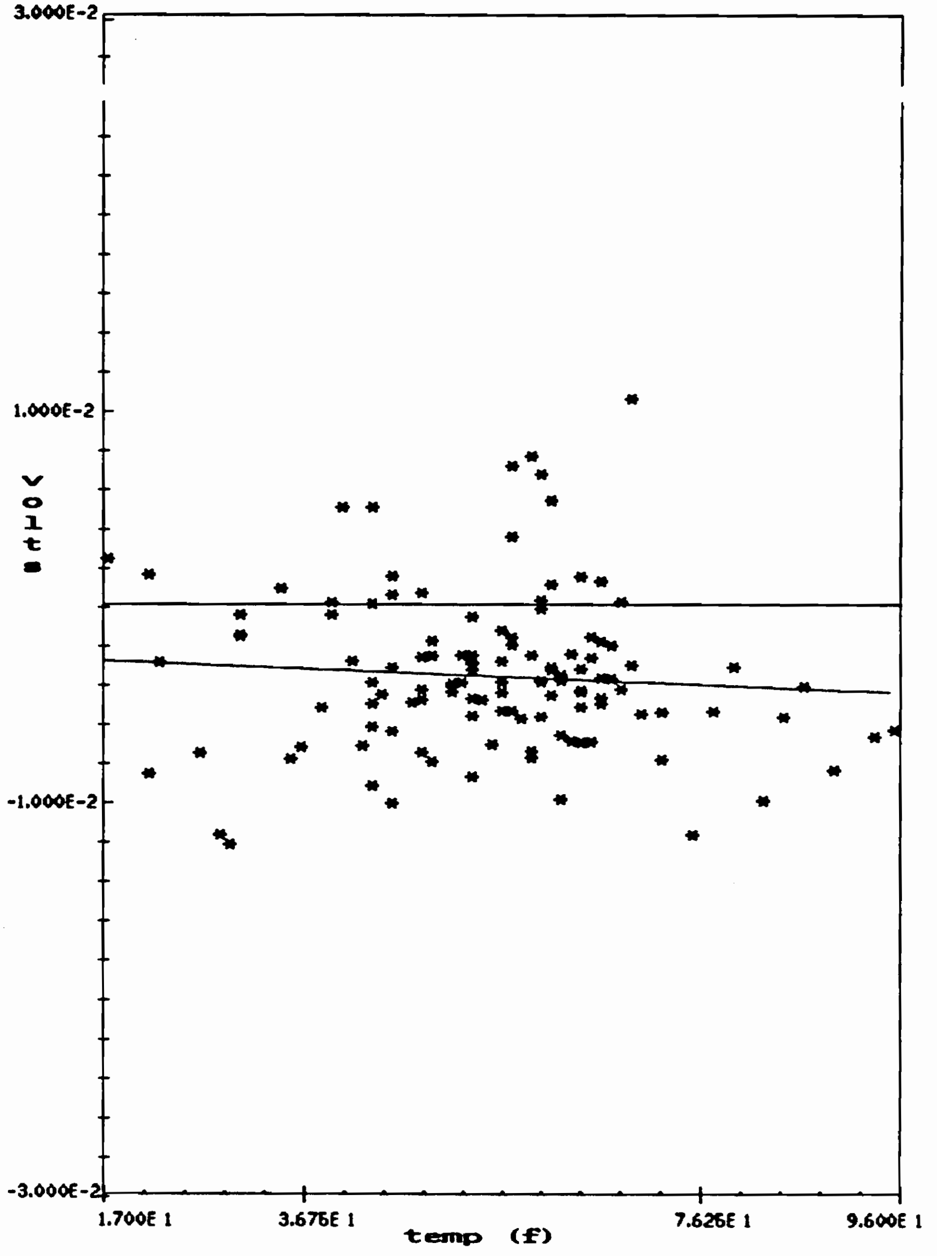

Figure 27. Plot of constant coefficient v/s temperature for CCVT

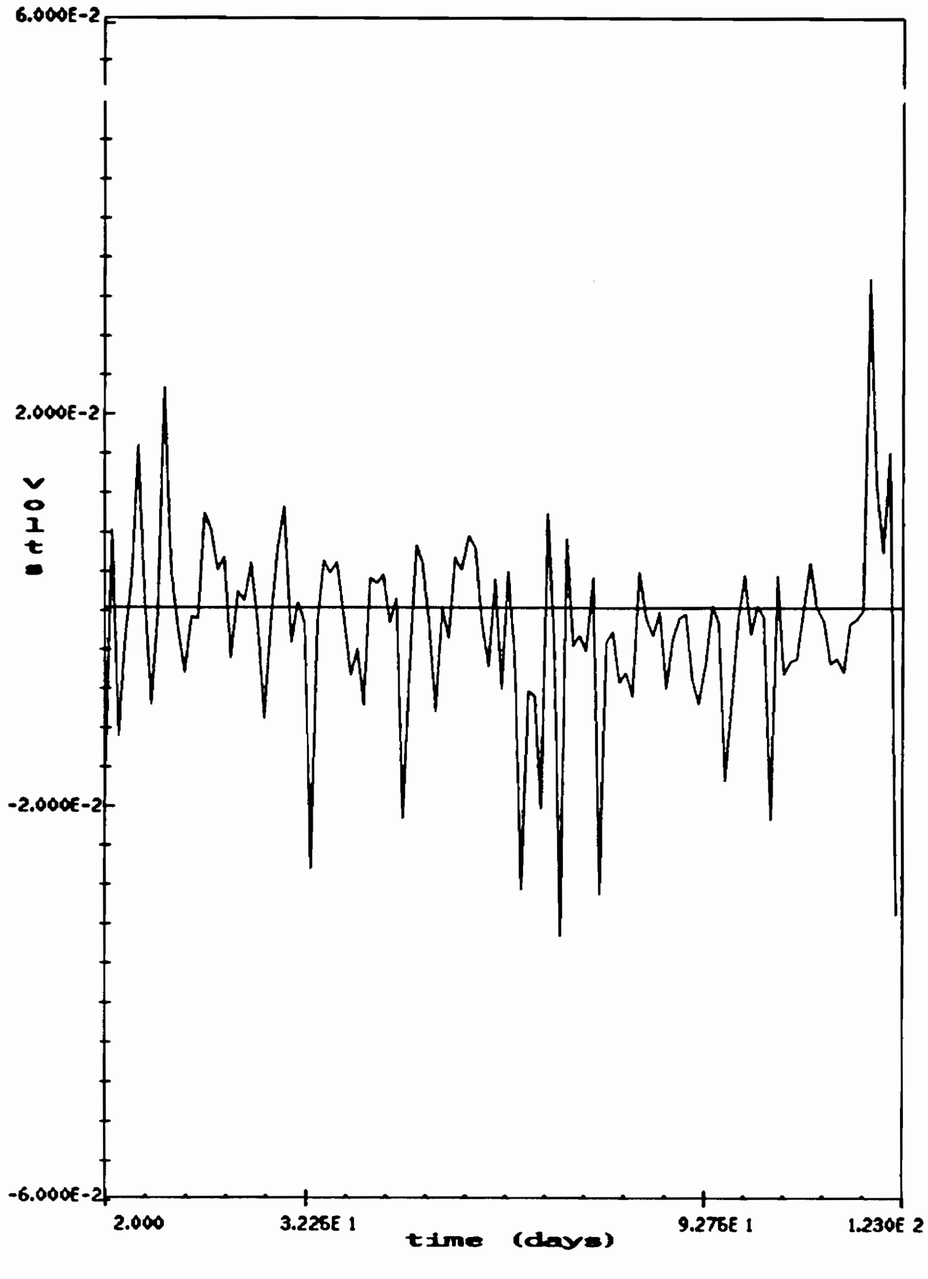

Figure 28. Plot of constant coefficient v/s time for Bushing VT

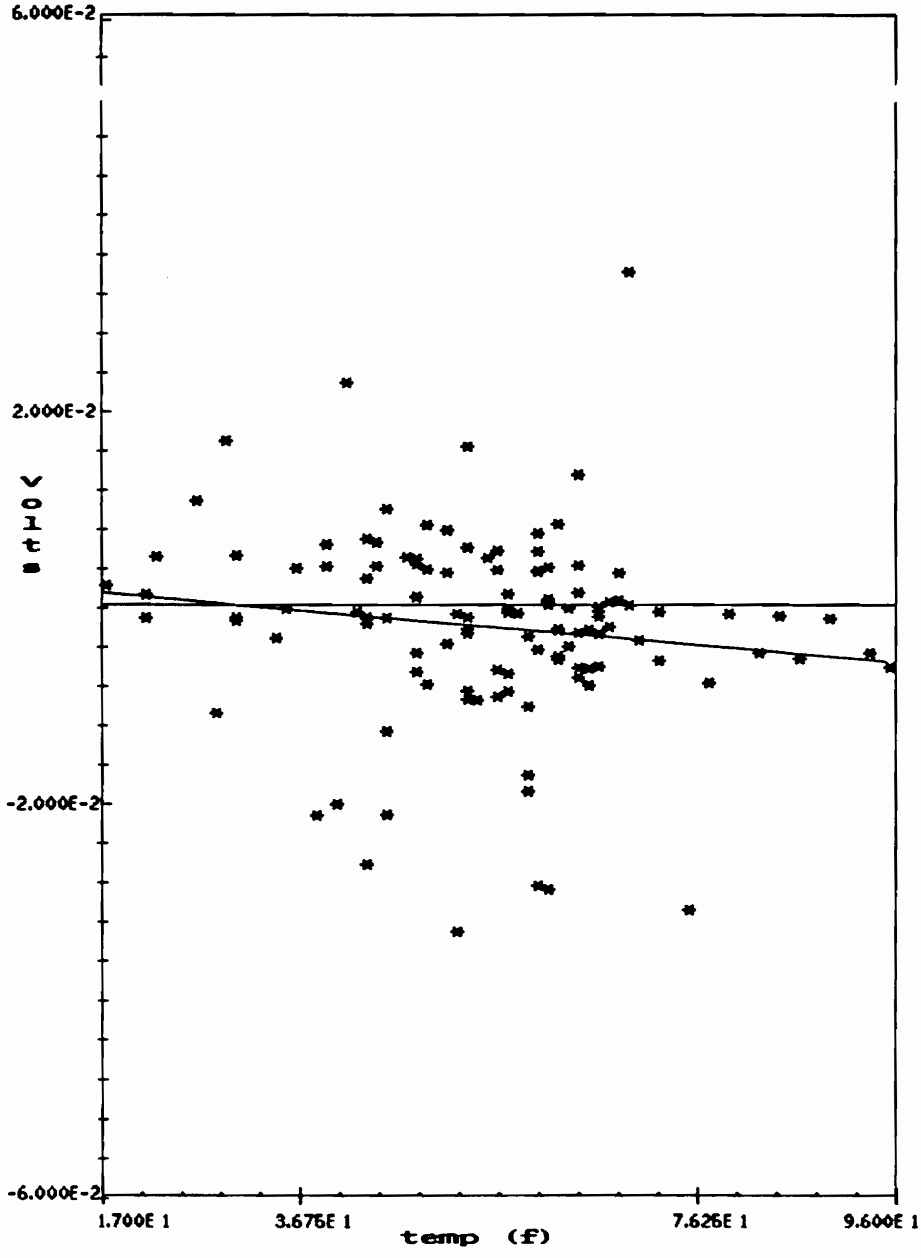

Figure 29. Plot of constant coefficient v/s temperature for Bushing VT

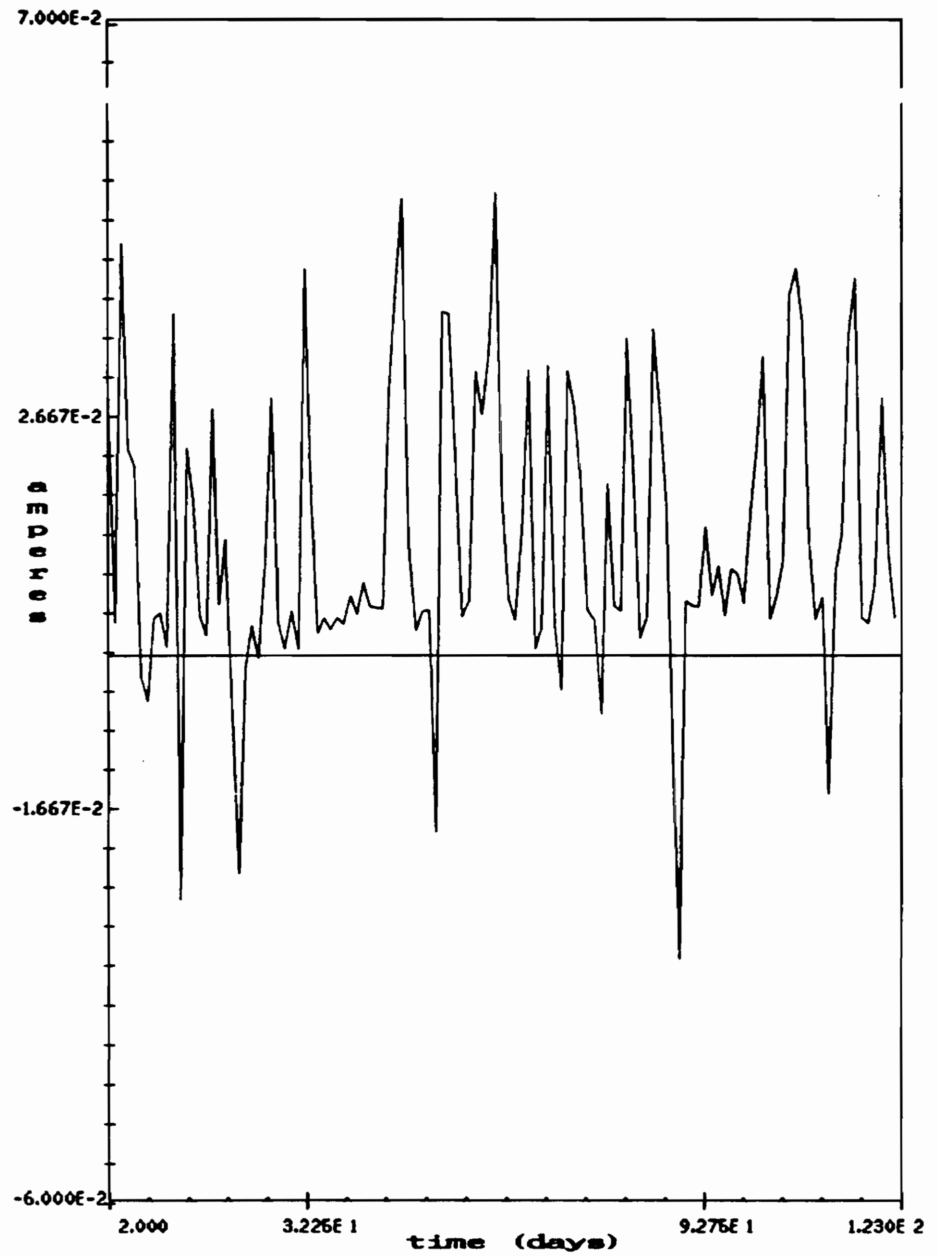

Figure 30. Plot of constant coefficient v/s time for Relaying CT

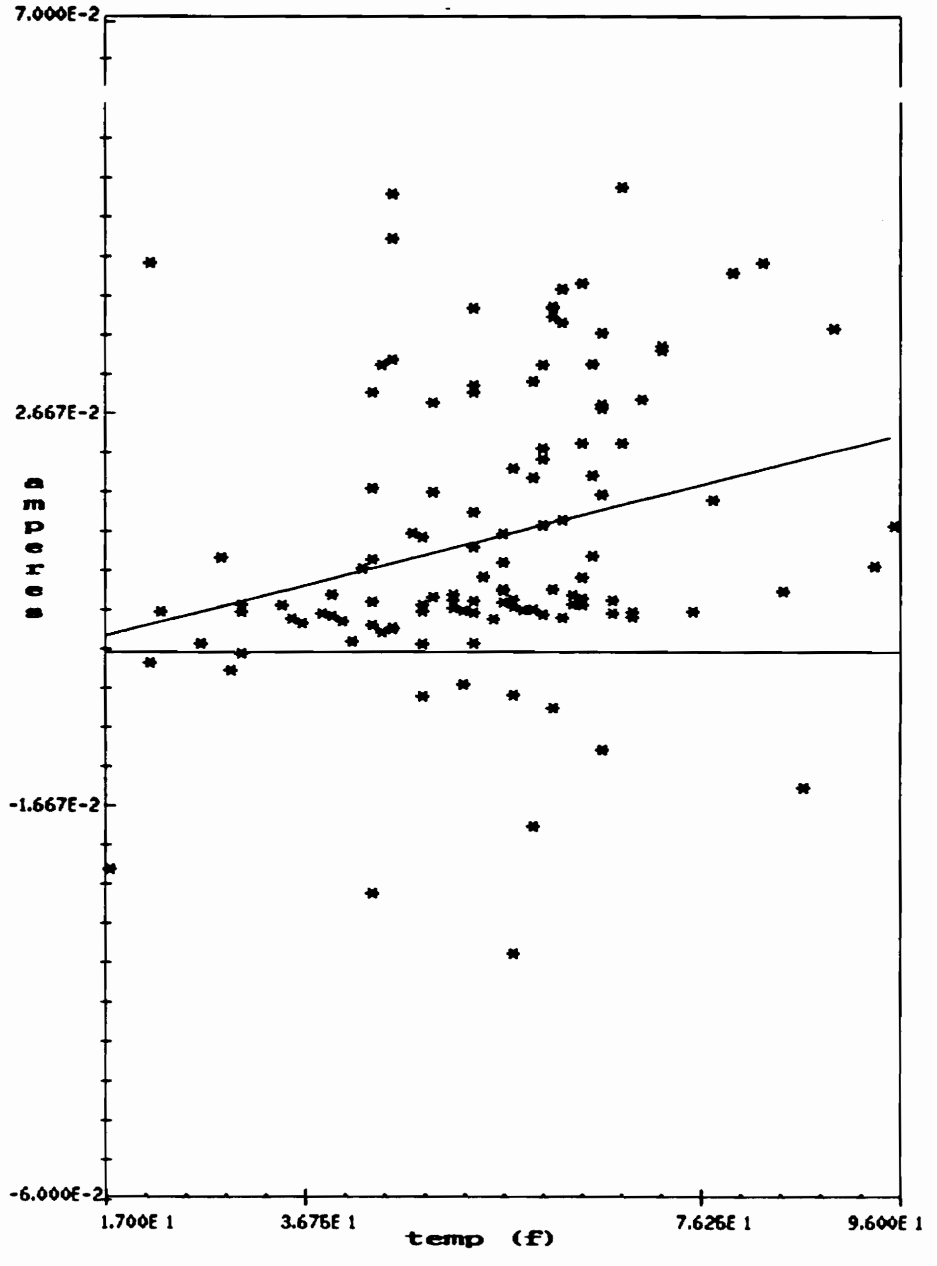

Figure 31. Plot of constant coefficient v/s temperature for Relaying CT

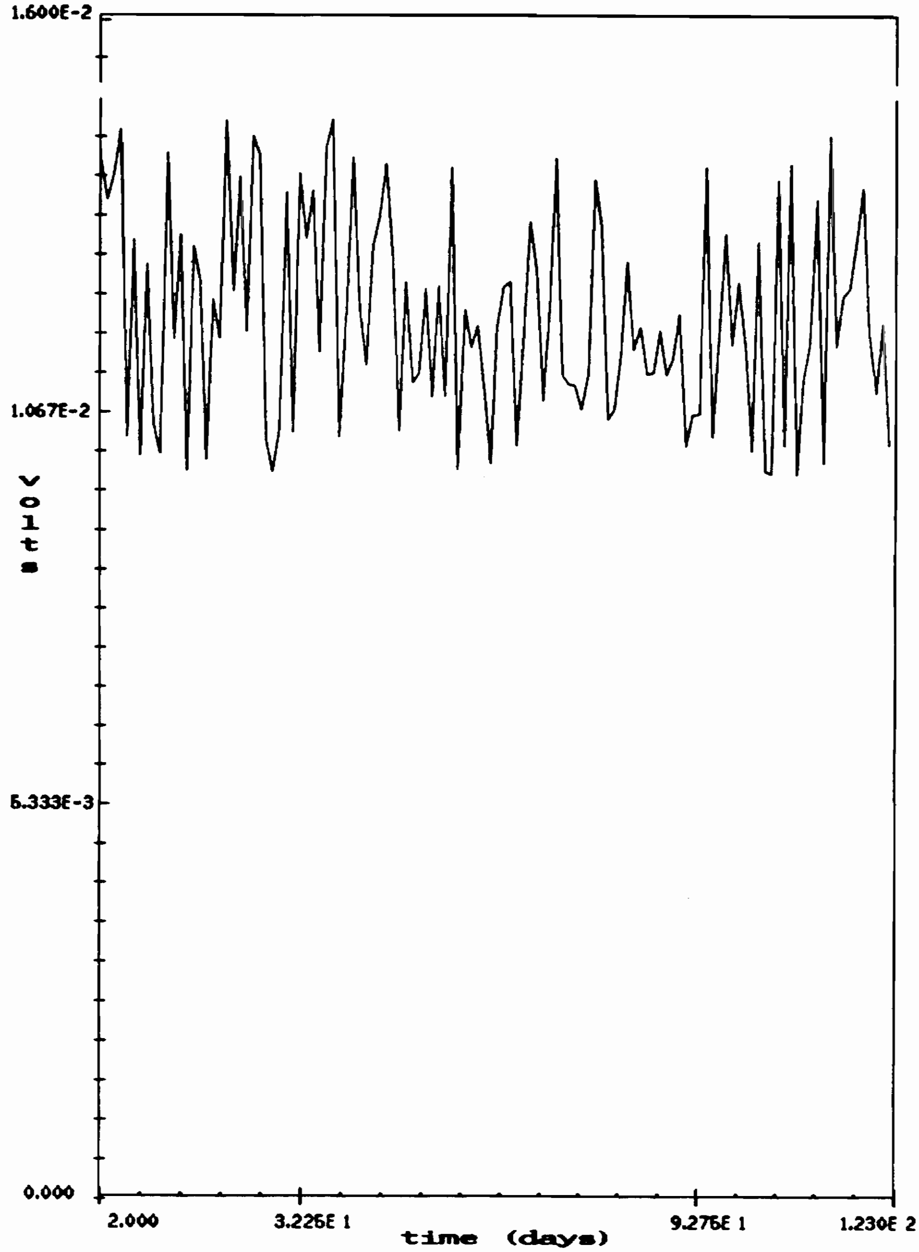

Figure 32. Plot of variance of noise v/s time for CCVT

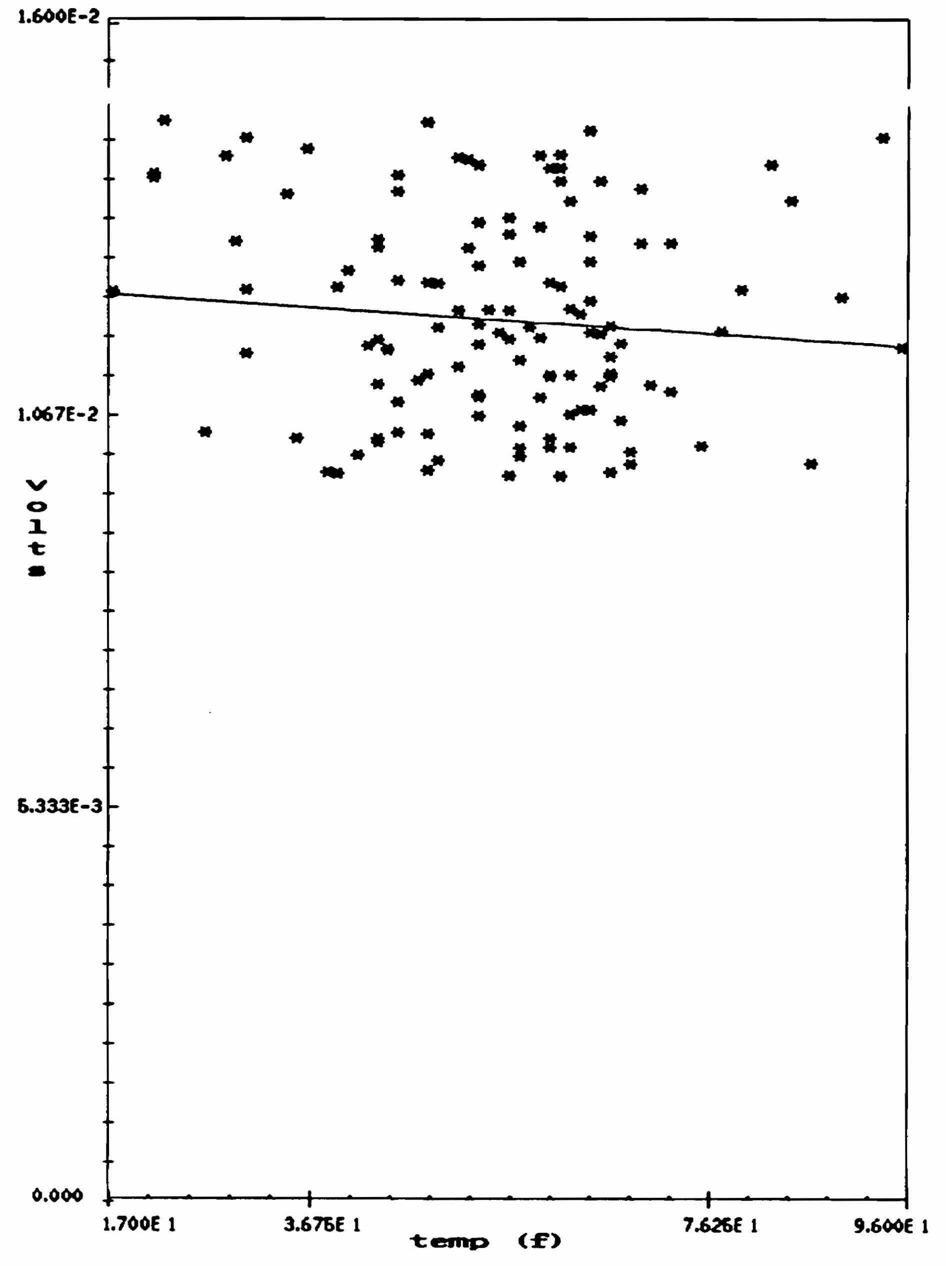

Figure 33. Plot of variance of noise v/s temperature for CCVT

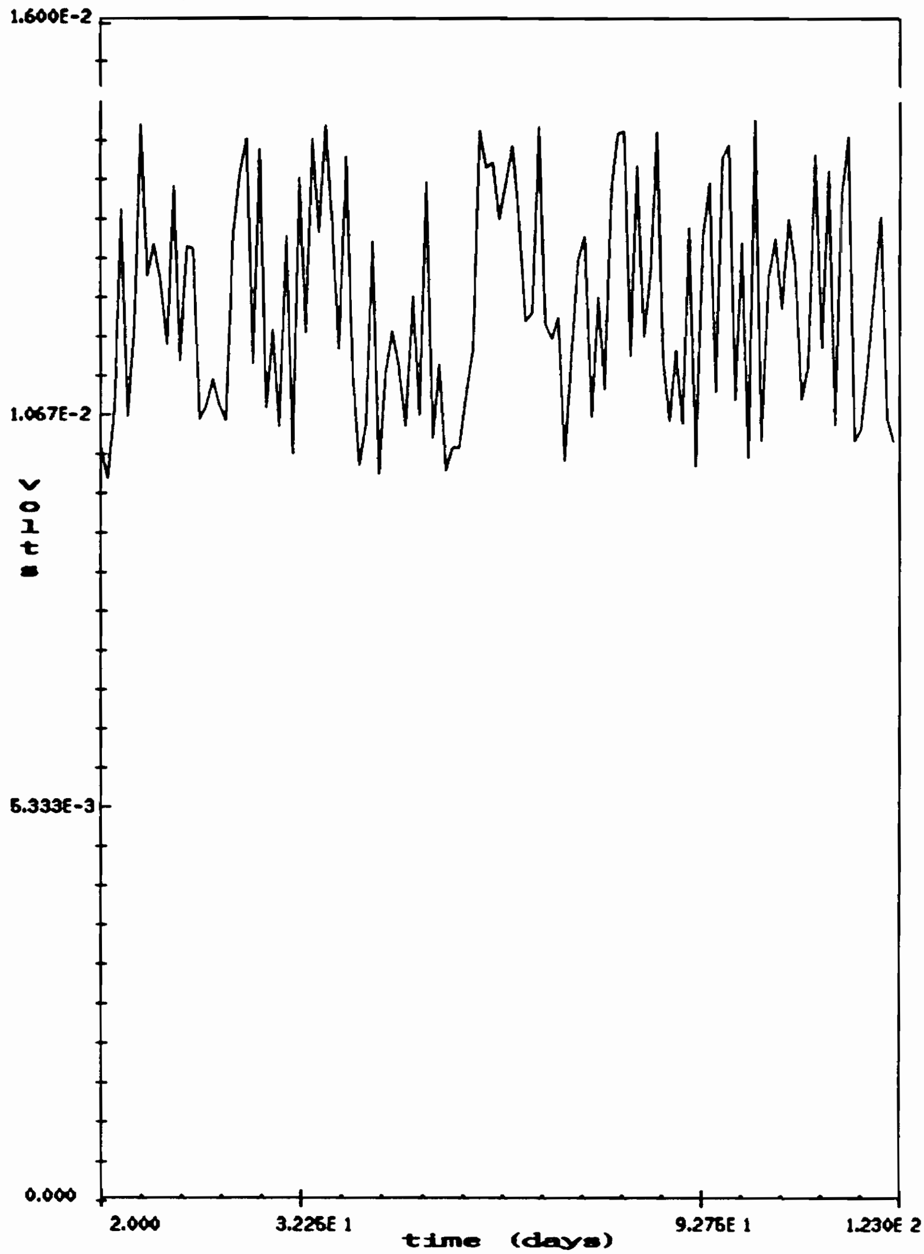

Figure 34. Plot of variance of noise v/s time for Bushing VT

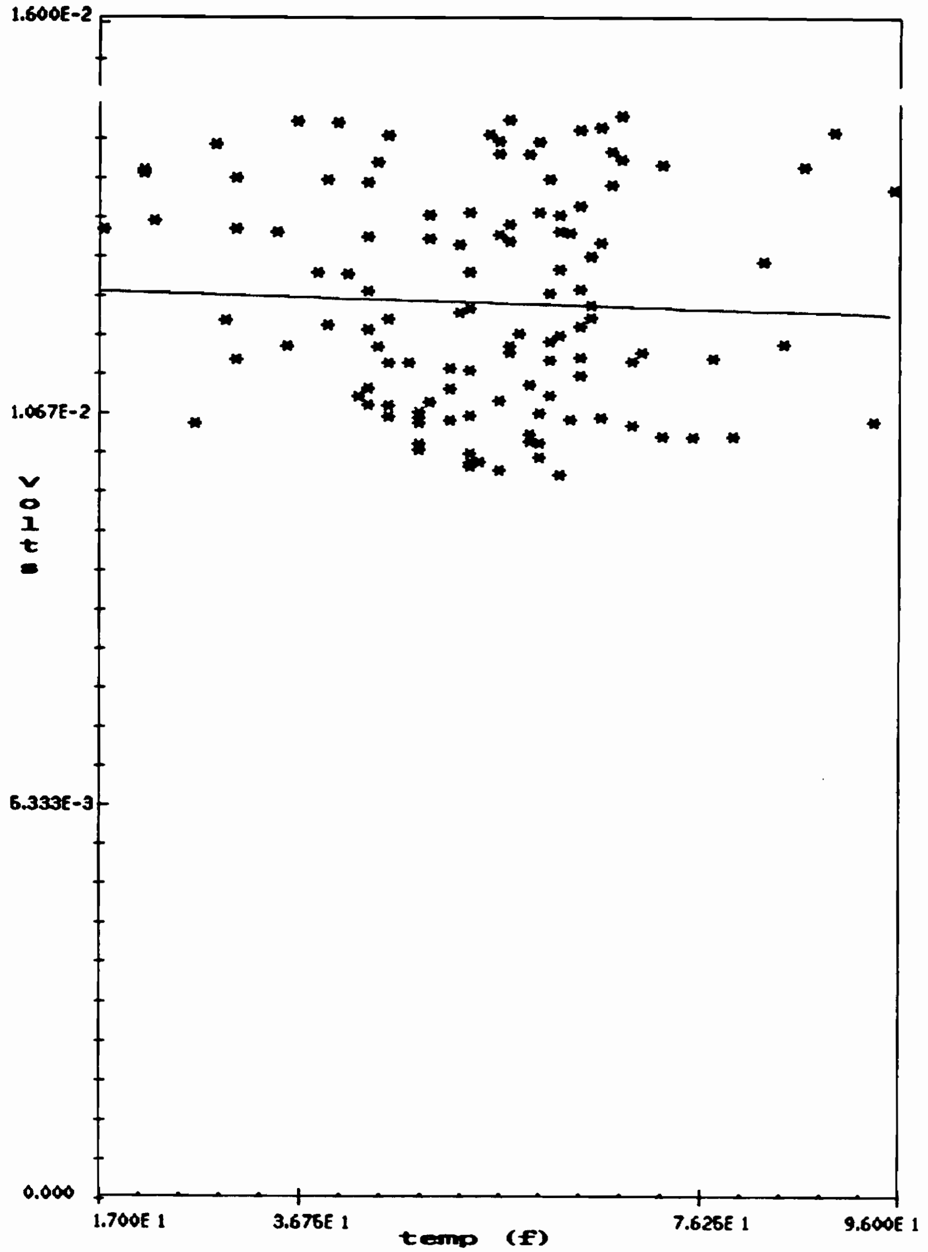

Figure 35. Plot of variance of noise v/s temperature for Bushing VT

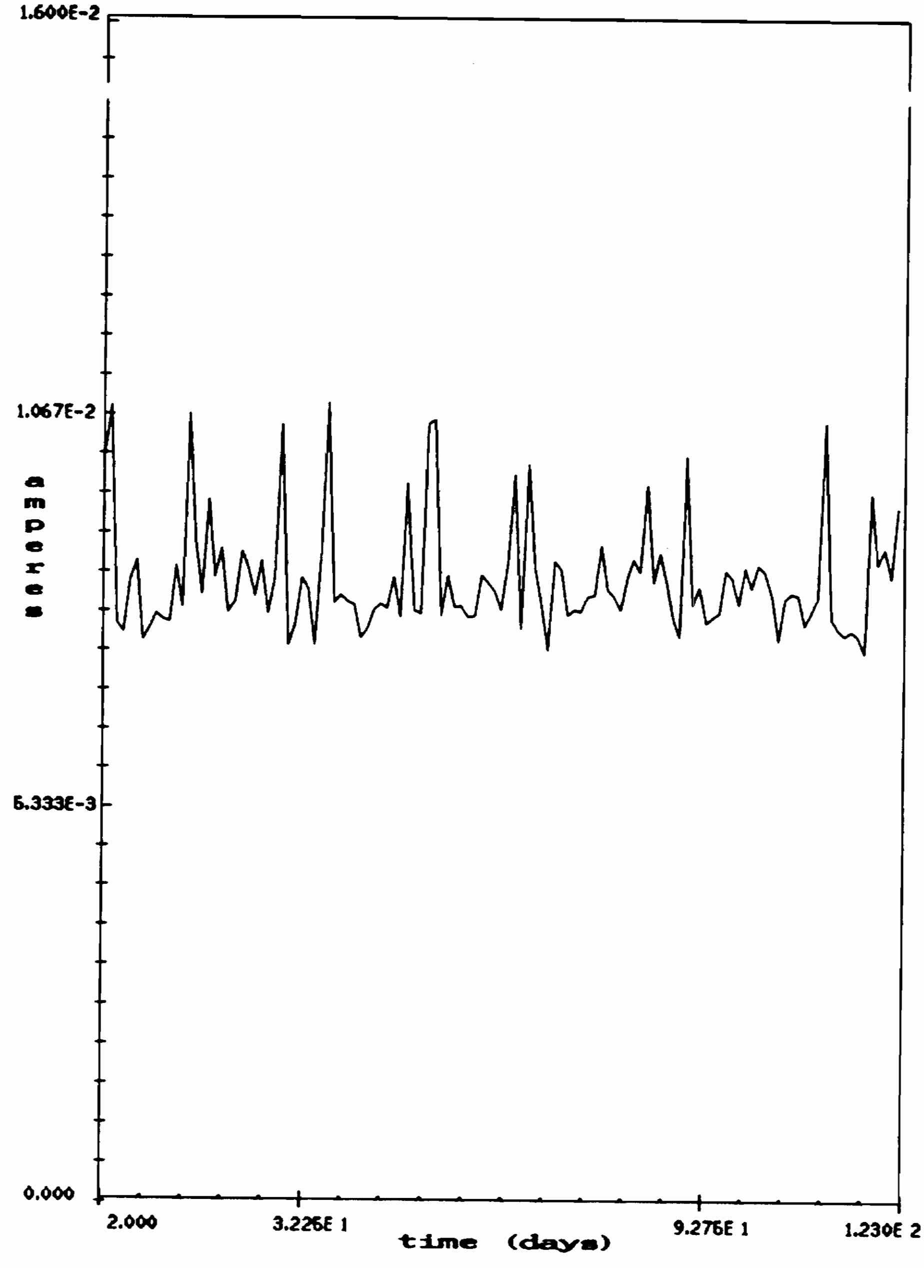

Figure 36. Plot of variance of noise v/s time for Relaying CT

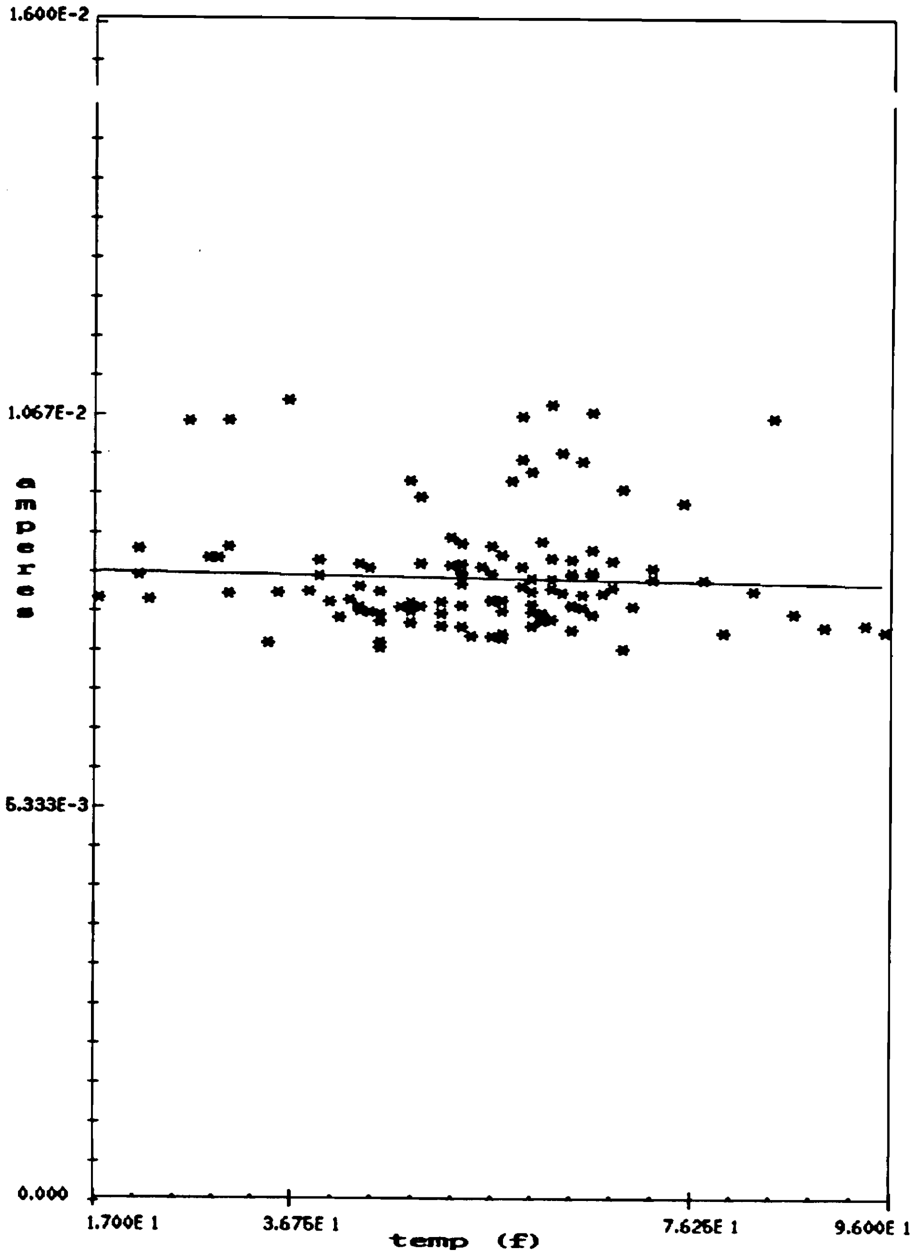

Figure 37. Plot of variance of noise v/s temperature for Relaying CT

```
The numbers are measured in A/D bits

A =  1.329448926938194751876233876386221E-0002
B = -2.776711197755754911712240943340271E-0015
C = -2.351374329718147180938147128269172E-0013
VARIANCE =   2.545690
MEAN = -3.428613772674500079425357530739338E-0007

A = -1.507832647870065880119664531349240E-0002
B = -3.588868367957051222521576575505345E-0015
C = -3.181372465199714112465386204881649E-0013
VARIANCE =   1.961546
MEAN = -4.542818717054287733254151701923204E-0007

A = -5.203255664250468855567951336134976E-0003
B = -1.873976236161482672610131140990276E-0014
C = -3.764403735486557149254619407997036E-0012
VARIANCE =   2.091556
MEAN = -2.392550098262177776756681591863569E-0006
```

Figure 38. The error coefficients for the data in Appendix A.

```
The numbers are measured in A/D bits

A =  1.329448926938194751876233876386221E-0002
B = -2.776711197755754911712240943340271E-0015
C = -2.351374329718147180938147128269172E-0013
VARIANCE =    2.545690
MEAN = -3.428613772674500079425357530739338E-0007

A = -1.507832647870065880119664531349240E-0002
B = -3.588868367957051222521576575505345E-0015
C = -3.181372465199714112465386204881649E-0013
VARIANCE =    1.961546
MEAN = -4.542818717054287733254151701923204E-0007

A = -5.203255664250468855567951336134976E-0003
B = -1.873976236161482672610131140990276E-0014
C = -3.764403735486557149254619407997036E-0012
VARIANCE =    2.091556
MEAN = -2.392550098262177776756681591863569E-0006
```

Figure 38. The error coefficients for the data in Appendix A.

Chapter 7. Conclusion

7.1 Introduction

The following sections review the thesis and draw some conclusions. Also in the last section two methods are suggested to improve and broaden the scope of the thesis.

7.2 Discussion of Results

1. The data collected over three months shows some definite trends in the error of the relaying CCVT, Bushing transformer, and the relaying CT. The mag-

nitude of the first coefficient in the error model is dependant on the ambient temperature to some extent.

2. The error model was selected as $\varepsilon = av + bT + c + \eta$ for voltage transformers and $\varepsilon = ai + bT + c + \eta$ for current transformer. The second error coefficient " b " was of the order of 10^{-6} volts per kelvin or amperes per kelvin for all transducers. Therefore the error caused by temperature changes would be of the order of 10^{-6}, which is insignificant; since the error would be much less than the resolution of the A/D converter. Therefore we can conclude that the voltage and current measurements are not affected by instantaneous temperature changes.

3. The first coefficient " a " however changes with the temperature. This means that if we calibrate relaying CTs or the VTs, the calibration will be subject to changes in the ambient temperature. As shown in the previous chapter the Bushing Voltage transformer is most sensitive to temperature changes, while the CCVT is least sensitive to temperature changes. The first coefficient of a CCVT decreases with an increase in temperature. This trend is more consistent than that found for a CT or Bushing VT.

4. From the point of view of a computer relay, if we intend to rectify the measurement errors in software, we may have to take the ambient temperature

readings to make changes in the first coefficient. If this is not done, the measurements will continue to have errors even after rectifying them. The amount of error caused by this is illustrated further in the following example. This may or may not be significant depending upon the application.

5. Let us assume that we calibrate the Bushing VT against metering VT used in this project, at 17 degrees Fahrenheit. From the data collected, this ratio would be 0.978 : 1.0. This ratio will change to 0.988 : 1.0 at 96 degrees Fahrenheit. This change will introduce a maximum error of 57 milivolts (12 A/D converter count), for an input signal of 4 volts r.m.s. This is the worst case error since the Bushing VT was found to be most sensitive to the temperature variations.

6. The d.c offset " c " was largest in relaying CT and lowest in case of CCVT. The offset does not show any trend in the variations. It is sometimes positive and sometimes negative. The magnitude of the d.c offset varies randomly if observed over a period of time or if seen over a range of temperature variation. In case of relaying CT the magnitude was on an average 25 miliamperes, while in case of Bushing VT it was around 10 milivolts. For CCVT the d.c offset was only around 5 milivolts.

7. The d.c offset or mean of the random noise is calculated over a day, which is very long period of time. Also the variance of the noise was around 15 milivolts. Therefore we can assume that this offset is fairly constant over a power frequency cycle. The computer relays which use phasor algorithms will not be affected by this error, since it will be averaged out over the cycle. Therefore, as far as the computer relays are concerned the d.c offset or the mean of the noise will not affect the computation.

8. The variance of noise does not show any kind of trend over a span of time or over a range of temperature variations. The " σ " of noise is around 15 milivolts in case of the Bushing VT and CCVT, while in case of the CT the noise is around 5 miliamperes.

9. The magnitude of the σ of noise is in the same range, as the range of the σ of noise found during calibration of the signal conditioner unit. This can be seen by comparing data in figure 4 to the figures 32 through 37. Therefore the noise can be attributed to the interface unit as well as the inherent quantization errors in the A/D and truncation errors in the microprocessor. The σ of 5 to 15 milivolts corresponds to approximately 4 to 6 A/D converter count.

10. The maximum voltage on the voltage channel was found close to 6.6 volts r.m.s, while the current maximum was around 6 amperes r.m.s. Therefore the noise is approximately 0.6 percent of the r.m.s value of the input signals.

11. This noise is a measure of the error which cannot be accounted for, using the present model. Therefore if the present model is used to rectify the errors in the relaying transducers, the errors will be reduced, but cannot be eliminated completely. A different model for the error or a better method of collecting and processing the data may have to be used to investigate this further.

7.3 Future developments

As this is the first research project undertaken to collect data from the field for error estimation in different transducers, there is a wide scope of improvement in future projects of this nature. The project was developed within the constraint of the available hardware and communication equipment. These can now be improved upon with faster and cheaper hardware.

7.3.1 Addition of new hardware

As described briefly in chapter 2, the data can be compressed as a histogram using additional memory. The price of memory is going down, therefore in the future it may be possible to add this extra memory to the existing hardware. The additional memory needed is about two megabytes of RAM. Also, we can save on communication costs by adding an external disk drive or an external hard drive to the field computer. This hard drive can be driven by a new microprocessor (Motorola 68030), or we may locate an IBM compatible machine on site. When the histogram in the RAM of the measuring unit gets full, the measuring unit can dump the histogram in the hard drive. The speed of storage would be about 16 times faster than what is achievable over a telephone line. Also, the histogram itself can be compressed further, depending upon the number counters having zero values.

The data collected in such a way can be retrieved periodically, say every three months, depending upon the space available on the hard drive. This is an easy method, which can reproduce the collected data without loosing any significant information. Also, the assembly language program required will be shorter and simpler than the one used in the present project. However, as mentioned before, the method requires additional hardware.

7.3.2 Expanding the error model

The second improvement would be the extension of the implemented error model. We can extend the existing error model to accommodate the nonlinearity. This can be achieved by assuming a polynomial error model. A more appealing method would be to put all possible values of the voltage and current as parameters. In other words, for voltage transducers there would be 4096 voltage coefficients each representing distinct voltage values the A/D converter output can have.

The instantaneous temperature as found in this project does not have any effect, however the variation in temperature has a small effect on long term basis. This effect can be measured by taking the average temperature over a few minutes as the temperature parameter instead of measuring the temperature every sample time.

This method is computationally intensive, as the number of parameters increases the dimension of the matrix to be calculated increases, as explained in chapter 2. If the size of the matrix becomes too large we may not have enough time to finish the calculations. However with a new microprocessor such as the Motorola 68030, which is about four times faster than the one used in this project, and by using some well known techniques for sparse matrix manipulations, this can be done. The only hardware change would be to replace the slower microprocessor now being used by a newer and faster microprocessor. The cost of the new microprocessor is comparable to the older one. The software for this method however is much more challenging, and it will take many innovative techniques before it can be developed completely.

Appendix A

Sample Data File

The following is the data collected from the field computer on April 11th, 1990. The numbers are as measured by the A/D converter. The first column is the voltage from the metering VT, the second column is voltage from CCVT, the third column shows voltage from Bushing VT, the fourth column shows the current measured by metering CT, the fifth column shows the current from the relaying CT. The last column shows the temperature measured. The temperature channel shows a small noise of fundamental frequency. The noise is taken care of by taking average of temperature over 12 samples and keeping it constant for the 12 samples.

378	378	382	314	312	-1194
1264	1286	1254	388	386	-1192
1846	1874	1802	348	348	-1190
1934	1950	1888	224	225	-1188
1474	1486	1462	33	32	-1185
604	618	612	-168	-170	-1182
-377	-378	-384	-320	-318	-1184
-1260	-1285	-1260	-394	-392	-1190
-1848	-1875	-1810	-354	-352	-1190
-1936	-1954	-1892	-230	-230	-1190
-1466	-1486	-1460	-36	-40	-1194
-604	-626	-614	163	162	-1196
376	376	380	314	312	-1194
1265	1290	1260	388	388	-1192
1848	1874	1806	348	344	-1188
1936	1951	1886	227	222	-1186
1467	1480	1454	32	32	-1186
605	618	612	-167	-168	-1186
-374	-378	-382	-318	-318	-1182
-1266	-1294	-1265	-394	-394	-1186
-1849	-1875	-1810	-352	-354	-1188
-1934	-1950	-1892	-226	-228	-1194
-1466	-1485	-1458	-34	-36	-1195
-602	-627	-614	164	162	-1194
372	374	378	314	310	-1196
1266	1294	1262	390	386	-1194
1848	1874	1808	349	346	-1190
1936	1950	1888	226	224	-1186
1466	1480	1454	32	32	-1185
596	612	602	-168	-170	-1184
-382	-382	-389	-322	-318	-1185
-1260	-1288	-1262	-394	-392	-1186
-1845	-1878	-1812	-353	-350	-1188
-1937	-1953	-1892	-230	-230	-1193
-1465	-1481	-1454	-34	-38	-1194
-598	-624	-609	164	164	-1196
380	378	384	316	310	-1194
1270	1296	1264	388	386	-1191
1848	1878	1806	348	344	-1188
1934	1950	1886	226	222	-1188
1464	1474	1452	30	31	-1186
604	616	608	-165	-170	-1184
-380	-380	-386	-318	-318	-1186
-1271	-1294	-1268	-394	-394	-1188
-1848	-1878	-1808	-354	-352	-1190
-1932	-1951	-1890	-230	-226	-1192
-1462	-1482	-1458	-34	-36	-1194
-592	-614	-606	168	164	-1194
386	386	388	316	314	-1196
1268	1288	1260	390	388	-1194
1854	1878	1808	348	346	-1190
1933	1950	1886	226	222	-1186
1458	1474	1446	28	28	-1184
594	608	602	-171	-172	-1184
-382	-386	-390	-322	-320	-1184
-1265	-1290	-1266	-393	-394	-1186
-1852	-1878	-1814	-352	-352	-1188
-1936	-1954	-1890	-232	-228	-1192
-1460	-1478	-1452	-36	-35	-1194
-592	-616	-604	164	164	-1194

382	384	388	317	312	-1193
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1849	1876	1808	346	346	-1190
1934	1946	1886	224	222	-1188
1462	1474	1448	30	28	-1186
590	604	594	-170	-172	-1184
-390	-392	-398	-320	-318	-1186
-1268	-1297	-1268	-394	-394	-1188
-1850	-1882	-1814	-352	-350	-1190
-1934	-1950	-1890	-228	-228	-1190
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390	386	390	316	314	-1194
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1850	1879	1806	347	344	-1190
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1458	1470	1446	26	26	-1186
596	608	601	-170	-174	-1184
-386	-386	-392	-322	-320	-1184
-1274	-1298	-1272	-394	-394	-1186
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1454	1468	1444	26	26	-1184
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-1454	-1472	-1446	-32	-30	-1194
-588	-611	-598	166	166	-1194
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1456	1468	1446	26	28	-1188
584	596	590	-174	-173	-1184
-394	-398	-404	-323	-326	-1184
-1272	-1298	-1272	-394	-394	-1188
-1848	-1880	-1812	-352	-350	-1190
-1932	-1950	-1888	-229	-226	-1192
-1452	-1471	-1444	-30	-32	-1194
-586	-606	-598	168	168	-1194

References

1. Numerical Analysis (book), Lee W. Johnson, R. Dean Riess

2. A new measurement technique for tracking voltage phasors, local system frequency, and rate of change of frequency, A.G.Phadke, J.S.Thorp, M.G.Adamiak, T-PAS MAY 83 1025-1038

3. One Line Diagram Cloverdale 500/345 Kv substation, Dr. No. AP-2627-1000-5, American Electric Power Service Corporation

4. Microtech ASM68K VR 6.0 Cross Assembler and Linking Loader

5. MVME 133A-20 VME module 32-bit Monoboard Microcomputer User's Manual, Motorola Inc.

6. MC68020 32-bit Microprocessor User's Manual, Motorola Inc.

7. MC68881 Floating-Point Coprocessor User's Manual, Motorola Inc.

8. User Manual DT1401 Series Data Translation

9. Microsoft Macro Assembler VR 5.1

10. IBM PC Maintenance and Hardware User's Guide

11. Intel Assembly Language 8086 (book)

12. Programming in VAX Fortran VR 4.0 Digital Software

13. Instrumentation Transformers ANSI/IEEE C57.13-1928

14. Guide for field testing of Relaying Current Transformers ANSI/IEEE C57.13.1-1981

15. Instrument Transformers for metering purposes ANSI/IEEE C12.11

16. Requirements for Instrument Transformers USAS C57.13-1968

17. Hayes Modem User's Guide

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