INTERNAL DISCHARGES IN HIGH VOLTAGE TRANSFORMERS
A COMPARISON OF MEASUREMENT
AND CALIBRATION METHODS

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ABSTRACT

This investigation is based on simulated tests done on a transformer. The L.V. winding is shown to be suitable for qualitative discharge measurements; further work is necessary to test for quantitative significance. The H.V. winding response to pulse trains is presented and the importance of using wide band instruments and pulse counters pointed out. Different detection networks are studied and the effectiveness of pulse calibration shown.

PREFACE

While the subject of internal discharges has long been studied, it is only recently that more attention has been devoted to it and its finer points understood.

Until the introduction of E.H.V. in power systems most transformers operated with internal discharges more or less satisfactorily. With the introduction of E.H.V. transformers, economic considerations made higher operating stresses essential. This demanded greater attention to the control or elimination of internal discharges.

However, much fundamental work remains to be done. This investigation concerns itself with the fundamental aspects of measurement and detection problems. The data presented is based on simulated tests and further work on transformers of differing design parameters will be rewarding.

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CHAPTER ONE

INTRODUCTION

The phenomenon of internal discharges in transformers has received widespread attention in the past few years. While various coupling circuits have been devised for the detection of these discharges there seems to be little or no agreement on the units of measurement, calibration procedure and essential circuit characteristics. As a consequence, standardization of test results is impossible. Yet another aspect of the problem is the validity of existing calibrating techniques in interpreting internal discharge magnitudes at voltage levels beyond inception. Moreover all present circuitry[1] is designed to be coupled to the line end of the high voltage winding. This in itself can pose practical problems.

The aim of the present investigation is threefold.

(a) To investigate the use of the L.V. winding for the detection of discharges.

(b) To study the response of the H.V. winding to pulse trains.

(c) To compare the existing different methods of detection with a view to examining the possibility of standardizing test results.

As an introduction, this chapter is devoted to the basics, i.e. definitions and fundamental phenomena associated with internal discharges. Chapters Two, Three and Four deal with the three main aspects of the investigation as detailed in the preceding paragraph

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[1] An exception being the so-called neutral current method.

and in that order.

1.1 DEFINITIONS:

Whenever an electric discharge occurs which does not bridge two electrodes, it is referred to as a partial discharge. Depending on the location it may be further classified as an internal or a surface discharge. Further, when internal discharges occur in voids, cavities or inclusions, they may be referred to as "cavity discharges". The term "corona discharge" or "internal corona" used in this connection is actually a misnomer and its use is not recommended. So also is the use of the term "ionization" or "internal ionization".

The mode of formation of discharges[2] is well known and will not be repeated here. Discharges give rise to phenomena such as light, heat, chemical transformation, ultrasonic noise and electrical disturbances. The ultrasonic noise generated may be used for locating the discharge site with good accuracy. Electrical disturbances are utilized to detect discharges and may find possible future application in the location of discharges. Chemical transformations and thermal effects cause progressive deterioration of the insulation adjacent to the discharging cavity.

The electrical disturbance manifests itself in the form of current pulses in the winding: these in turn being caused by step changes in the voltage whenever a discharge occurs. The current pulses produce voltages at the terminals whose magnitudes depend on the characteristics of the winding and the connected bushing.

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[2] Here and elsewhere the use of the word discharge implies an "internal discharge".

Generally, the magnitude is of the order of a few millivolts at the most. Thus it is not the magnitude but the cumulative effects of other secondary phenomena which are detrimental to the insulation.

When an alternating voltage is applied to a transformer winding discharges may recur every half cycle. During each half cycle many discharges may occur. At the inception voltage there are relatively few discharges per half cycle. As the voltage is raised the magnitude of the discharges remains almost constant but the number of discharges per half cycle increases. This may be moreso if, at the higher voltages, other potential sites begin to discharge owing to the increased stress. The discharges can therefore be likened to pulse trains. The recurrent frequency of the pulse trains remains the same. This property may be made use of in running accelerated life tests at high frequencies.

When the voltage is lowered, the value of voltage at which discharges cease, called the extinction voltage, is usually 10 to 25 percent lower than the inception voltage. Also, if the voltage is held steady at a value above inception the discharge magnitude may vary considerably. This may happen when moisture or carbon formation results in the shorting of a cavity which occurs more readily when the discharges are severe. If the voltage is held at well above inception for a sufficiently long time, not only may the magnitude change but also the re-inception and extinction voltages which may now be higher by as much as ten percent. Also, the number of discharges per half cycle will vary. Again, such phenomena will be readily noticed if the discharges are severe.

Near inception, intermittent discharges may appear. As their name implies they do not occur regularly. At well above inception "wandering" discharges may appear. Such discharges do not occur at a uniform recurrent frequency.

1.2 SPECTRUM OF DISCHARGE:

The current pulses that are generated following a discharge have rise times between 10 and 100 ns [11] and durations of the order of 10^{-7} sec. [12]. The decay time is not as fast as the rise time. Such a pulse has essentially a broad spectrum which is quite flat in the MHz region. However, the spectrum measured at the terminals will differ from transformer to transformer owing to differing winding characteristics. The usual practise is to measure the frequency component at either 1 MHz or 500 KHz using narrow band instruments. That measurements made at such arbitrary frequencies can not be given precise quantitative significance has already been shown in previous work [1].

1.3 MODEL REPRESENTATION:

For simple dielectric slabs or capacitors the familiar abc model is an adequate representation of discharge phenomena. A transformer, however, is a complex network which exhibits behaviour varying with frequency. At the lower audio frequencies the series capacitances may be ignored and a lumped LC network results. Up to the critical frequency ($\omega_c = \frac{1}{\sqrt{CK}}$)[3] transmission line behaviour is exhibited. At frequencies above ω_c the series inductances act as open circuits and a capacitive network results.

Discharges in transformers can be of two types — winding to winding or winding to earth. In either case an abc representation is

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[3] C is the series (turn to turn) capacitance and K the shunt (turn to earth) capacitance.

possible at the discharge site. The abc circuit can be represented by a step wave generator in series with a capacitance. Thinking of the discharge source as a voltage source one can reduce this circuit to the voltage at the terminals in series with an impedance or as a current source in parallel with the same impedance. The nature of this impedance will vary with frequency.

1.4 OBJECT OF DISCHARGE TESTING:

Three points are of interest in any discharge test, namely the inception and extinction voltages and discharge variation characteristics with voltage. As yet the position is quite uncertain regarding the relation between discharge magnitudes, repetition rates and life of insulation. Thus inception and extinction voltages are of great interest because a voltage surge may cause inception and depending on the difference in inception and extinction voltages, the discharge may persist if the extinction voltage is less than the normal operating voltage. Another important factor is that the measurement of discharge magnitude is possible only at the terminals and the relationship between the discharge magnitude at the terminals and magnitude at the discharge site is by no means simple. Any effort at discharge measurement should therefore aim to record faithfully conditions presented at the terminals.

Mention may also be made of the difference between radio interference and discharge measurements. The only similarity, as per standards existing today, is in instrumentation and it ends there. Discharges occuring within a winding are not important at all from the point of view of radio interference owing to the attenuation suffered in traversing the winding. Acceptable levels of radio interference will vary from place to place but this is not so with discharge measurements made on transformers.

CHAPTER TWO

USE OF THE L.V. WINDING FOR DISCHARGE DETECTION

A discharge detection circuit which has to be coupled to the line end of the high voltage winding involves the use of an isolating capacitor. This can be either a high voltage gas capacitor or the bushing itself if it has a capacitance tap. Naturally the gas capacitor has to be discharge free at the test voltages, as also is the case with the bushing, otherwise discharges originating in this isolating capacitor may be detected with relatively little attenuation. At the higher voltages it may not only be difficult to procure a discharge free gas capacitor but also the investment can be considerable. Besides, when working at the higher voltages the natural tendency is to run long lengths of cable which may amount to considerable stray capacitance. If an external capacitor is used then corona free connections have to be made and the test set up is not readily available. These considerations prompted an investigation into the suitability of using the low voltage winding for the detection of discharges.

The low voltage winding has two ends both of which may be used for coupling the response. Polarity checks were made so that the ends could be identified readily. The end which has the same polarity as the line end of the high voltage winding will be referred to here after as "end C". The other end will be designated by the letter B. For ready comparison the response from the high voltage terminal will be obtained.

2.1 THE TEST OBJECT:

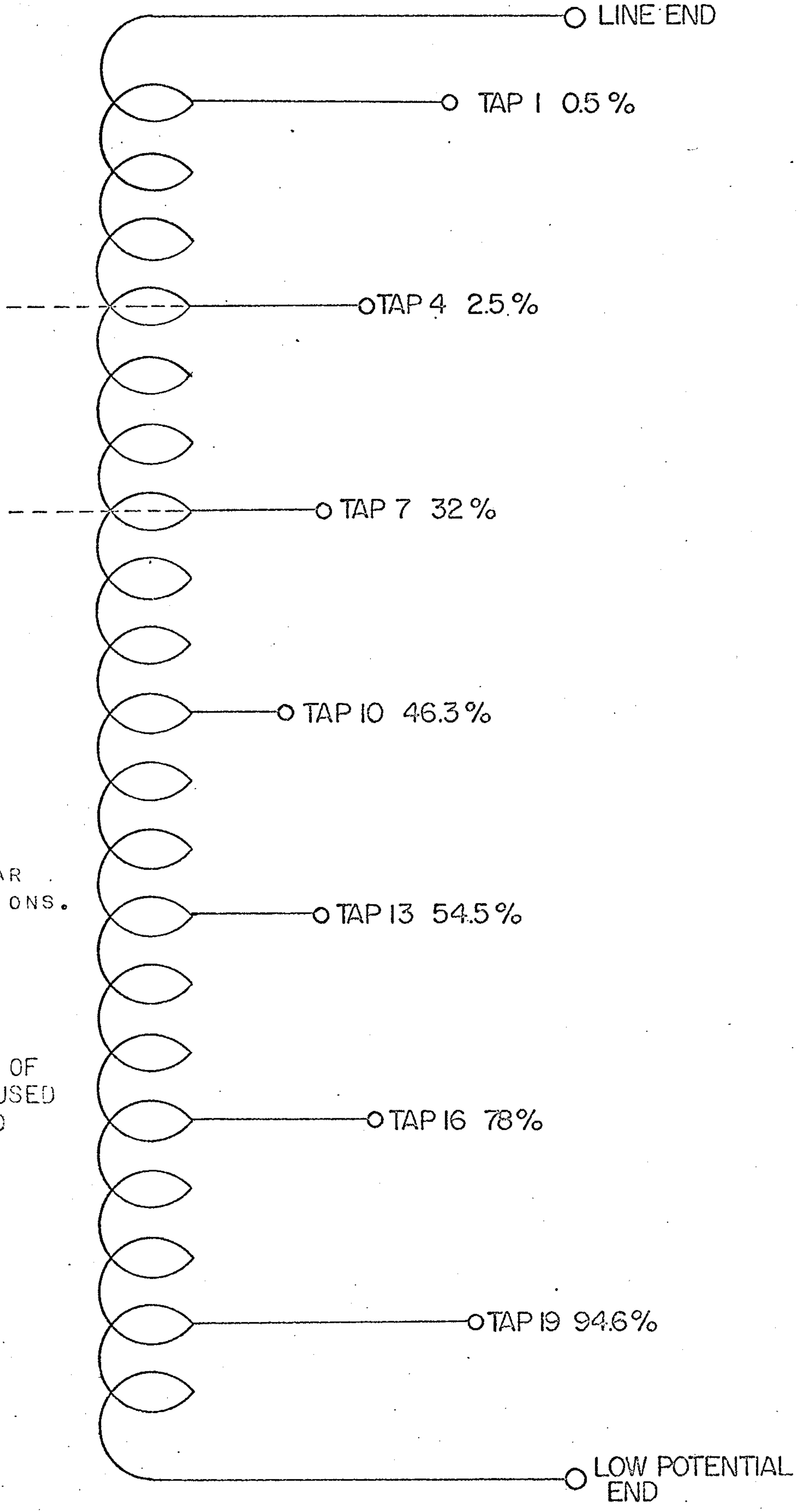
The transformer used was a single phase 200 KVA 2200v/80 Kv core type with the whole assembly lifted out of the tank. Thus a number of tap positions were readily available. A steel mesh of suitable dimensions to simulate the tank capacitance was fitted around the windings. As the bushing had been removed, a 500 pf mica capacitor was used to simulate it. The taps were not arranged uniformly along the winding; which was comprised of three different sections. Figure 2.1 illustrates the tap positions and the junction points of dissimilar windings.

2.2 SIGNAL GENERATOR:

The signal generator used was a Hewlett Packard model 214A pulse generator capable of giving output pulses 50v maximum amplitude into a 50Ω load. The pulse width could be varied from 0.05 microseconds to 10 milliseconds while the range of repetition rates available was from 10 cps to 1 Mc. The output could also be gated if desired.

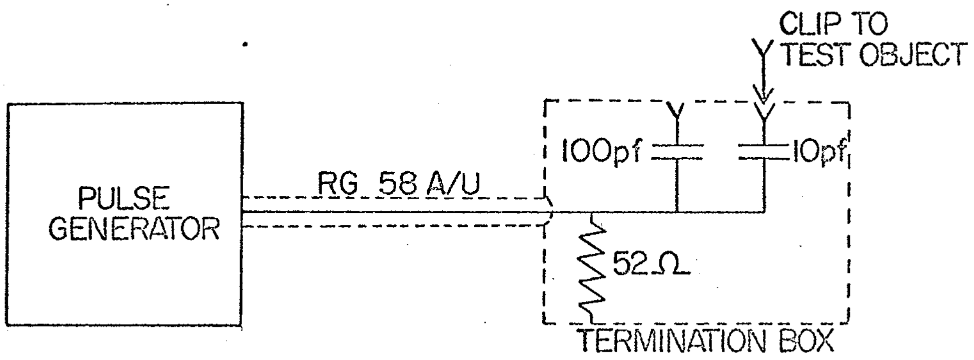
2.3 EXPERIMENTAL SET UP, TECHNIQUE AND RESULTS:

The scheme of connections of the test apparatus was as shown in Figure 2.2. As in previous work [1] [2] a modified R1155 communications receiver was used. The output could be displayed both on a CRO and a DC VTVM fed through a peak rectifying circuit. To enable continuous recording of the frequency spectrum an X-Y recorder was used. The X-axis received its supply from a potentiometer connected to the tuning shaft of the receiver. The X-axis therefore represented frequency. The Y-axis received its signal from the output of the peak rectifying circuit. When the input to the recorder was paralleled with the output

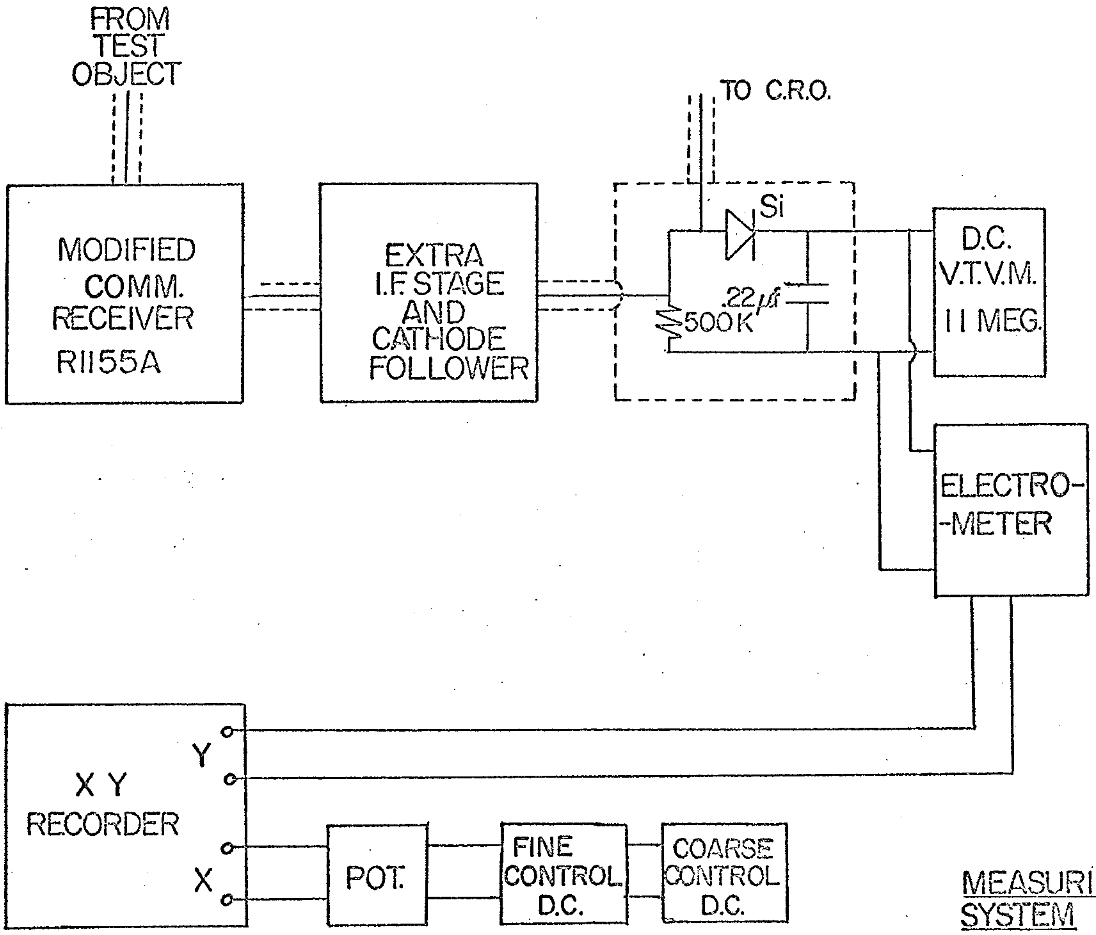


- FIGURES IN PER CENT INDICATE PER CENT WINDING FROM H.V. END.
- BROKEN LINES INDICATE JUNCTIONS OF DISSIMILAR TYPES OF WINDING SECTIONS.

FIG. 2.1 H.V. WINDING OF TRANSFORMER USED FOR SIMULATED TESTS.



PULSE SOURCE



MEASURING SYSTEM

FIG. 2.2 THE PULSE SOURCE AND THE MEASURING SYSTEM SET UP FOR MEASUREMENT WITH THE MODIFIED RADIO RECEIVER.

VTVM a fall in output resulted owing to loading effects. A Keithley vacuum tube electrometer (model 210A) was therefore used. This had a very high input impedance. The VTVM, however, was still kept connected so that output readings did not change. The electrometer was equipped with an output amplifier and the output terminals of this were connected to the Y-axis of the recorder.

The potentiometer chosen to drive the recorder was quite linear. However the frequency scale on the receiver is hardly so and this accounts for the non-linear frequency scale on all curves obtained from the recorder.

To obtain the H.V. response (the scheme of connections being as in Figure 2.2) pulses were injected into various taps from the signal generator through a 10 pf capacitor. The pulse width was set at 10^{-7} sec. - the order of discharge duration. The repetition rate was set at 120 c.p.s. This amounted to one discharge per half cycle. Care was taken to set the gain and input magnitude so that output readings did not exceed 7.0 volts on the output VTVM as this is the linear limit for the receiver used. Throughout the experiment the receiver gain was not altered. The frequency was varied slowly and continuously and curves obtained from the recorder. The output from the generator was then paralleled with the input to the receiver keeping the transformer connected and another recordogram obtained of output versus frequency. The receiver gain remained sensibly constant with time. Whenever there was an element of doubt the curves were discarded.

For the low voltage response the method remained exactly the same, the only difference being that the response was now coupled first to "end C" and then to "end B". When the response was coupled to end C, "end B" was earthed and vice versa. (Figure 2.3)

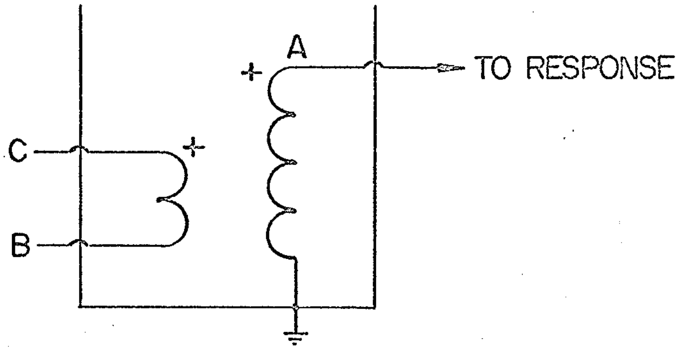
Typical recordings are shown in Figures 2.4 to 2.9.

The object is to obtain the relation between the magnitude of pulse injected and that at the terminals for various frequencies. The spectrum of the pulses being essentially flat in the MHz region, the recordogram obtained when the generator is paralleled with the input to the receiver should be a horizontal line. However, this is not the case owing to variation of receiver gain with frequency. Thus the recordograms themselves have little significance. Moreover, different values of inputs were used at different taps to ensure that the linearity limit of the receiver was not exceeded. The actual response curves were therefore obtained as follows.

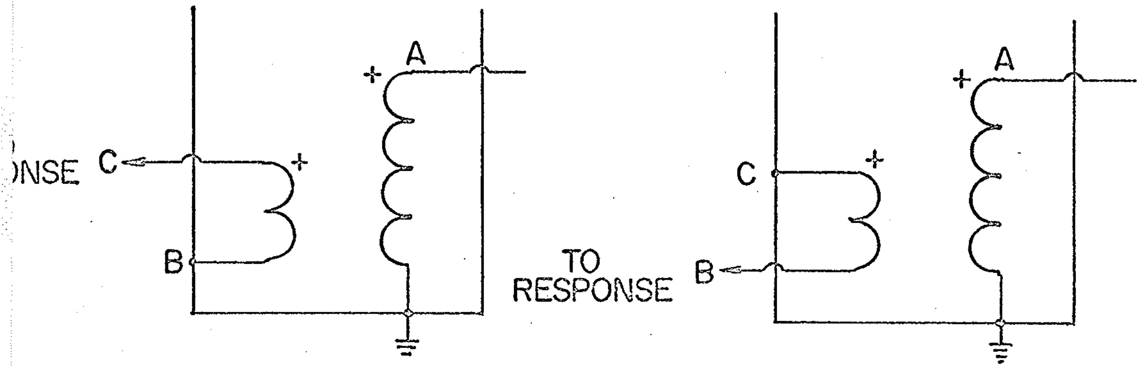
At a particular frequency let the output be V_1 volts when the input is V_2 at a particular tap. Also with the input of magnitude V_2' paralleled to the input to the receiver let the output be V_1' volts. If the receiver is worked in its linear range then, to get an output V_1 volts with the input paralleled with the input to the receiver the magnitude of the injected input should be $\frac{V_2'}{V_1'} V_1$. The unit response defined as

$$\left[\frac{\text{pulse input magnitude at a tap to give some output reading}}{\text{pulse input magnitude at input to receiver to give same output as in numerator}}\right]^{-1}$$

will be given by $\frac{V_2'}{V_1'} \frac{V_1}{V_2}$. The percent response is then $\frac{V_2'}{V_1'} \frac{V_1}{V_2} \times 100$. This is of course assuming that the recorder voltage sensitivity adjustment remains the same and also that the receiver is worked in its linear range. In the experiment the recorder voltage sensitivity was fixed.



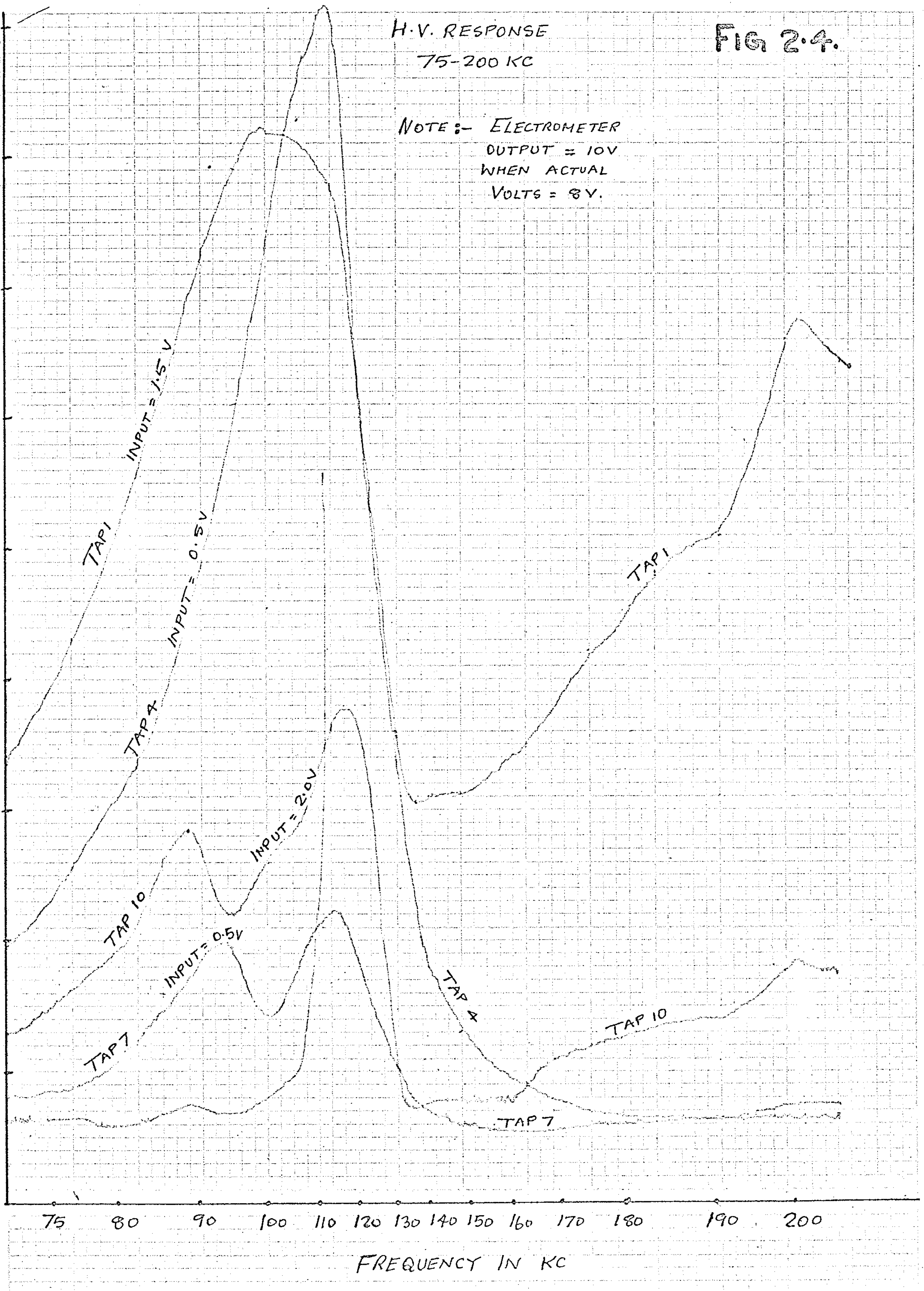
CONNECTION OF WINDINGS FOR H.V. RESPONSE



CONNECTION OF WINDINGS FOR L.V. RESPONSE

FIG 2.3 CONNECTION OF WINDINGS TO OBTAIN RESPONSE FROM H.V. AND L.V. WINDINGS.

TYPICAL RECORDOGRAM OF



H.V. RESPONSE
75-200 KC

FIG 2.4.

NOTE :- ELECTROMETER
OUTPUT = 10V
WHEN ACTUAL
VOLTS = 8V.