LOAD REPRESENTATION FOR TRANSIENT STABILITY STUDIES

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PREFACE

Very great advances have been made in the last few years in the ability to interconnect and in actual interconnections of the continent's power systems. This has created a need to study constantly increasing power systems with greater and greater accuracy. Great strides have been made in mathematical techniques and the application of computers to the study and prediction of system behaviour under transient conditions. While progress has been made in the ability to analyze very complicated relationships a very distinct gap has remained in the knowledge of load behaviour in general as well as during transient conditions. The reason for this has been the difficulty in obtaining meaningful results as well as the requirement of most utilities to disturb power users as little as possible. It was therefore undertaken to investigate load behaviour under rapid voltage changes of a small magnitude.

ABSTRACT

A description of the main types of loads, individually and in combination is given. Other authors' work on transient load representation is reviewed and summarized with their findings evaluated. The tests carried out by the author on the Manitoba Hydro system are described. The description of loads both electrically and geographically is reviewed. The techniques used in analyzing the results are detailed and the results are tabulated. Conclusions based on the data obtained are given and limitations described.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

LIST OF SYMBOLS

I = current in amperes
V = emf, potential difference, in volts
R = resistance in ohms
P = power in watts
n = speed in per unit
T = torque in per unit
s = slip in per unit
k = a constant or symbol for a thousand
f = frequency in hertz
Q = reactive power in kVA
k_I = constant which relates voltage to current
k_P = constant which relates voltage to power
k_Q = constant which relates voltage to reactive power
x_I = exponential power that current is a function of voltage to
x_P = exponential power that is a function of voltage to
x_Q = exponential power that reactive power is a function of voltage to
y = dependent variable
x = independent variable
Δ = change in a quantity
f = function of
A = constant
B = constant
C = constant
P_0 = initial value of power

V_0 = initial value of voltage

I_0 = initial value of current

Q_0 = initial value of reactive power

P_F = final value of power

V_F = final value of voltage

I_F = final value of current

Q_F = final value of reactive power

t = time in seconds

CHAPTER I

INTRODUCTION

The behaviour of electrical loads are well understood and described mathematically on an individual basis. However, the behaviour of electrical load in a modern utility system is not adequately understood because of the random nature of the load and the effect of the power system itself. At present, studies have not been carried out in sufficient detail to assess the load characteristics of power systems. This is particularly true of the short term variation of the electrical load when subjected to a changing voltage or frequency on the power system.

Work previously carried out by other authors has been limited in scope or confined to a small area. Because of the varying nature of loads, it is felt that no general representation can be used for all systems. This investigation is, therefore, primarily limited to the study of Manitoba Hydro loads at major stations. It was decided to choose major stations because the results would also include the effects of the sub-transmission system. At present whenever studies are carried out, individual loads of several stations are lumped at the major station busses without any attempt to take into effect the transmission lines and transformers connecting the major and distribution stations.

These lines and transformers between the major and distribution stations would tend to dampen out rapid voltage changes and the conditions that the loads would actually experience would not be as severe. The actual effect of placing the substation loads at the major station busses would depend on the load representation used. The load behaviour in the transient region (first thirty cycles after a disturbance) was selected for detailed investigation in order to obtain a clearer understanding of the effect of loads on a power system during transient swings.

It is very important to represent loads correctly for long range stability studies. If a representation is chosen that shows the system to be more stable than it actually is, operating problems will be encountered. Unexpected equipment tripouts will occur and often the only solution at that stage would be to impose load transfer limits on key lines. On the other hand if a particular representation shows a system to be less stable than it actually is, facilities are built that are not required and therefore money is wasted.

No attempt was made to write a computer program to use the findings in this study. Programs for transient stability studies of power systems are readily available and any attempt to duplicate these would be wasteful in time and effort.

Theory

Electrical loads can be divided into two main groups. The first of these are the so-called static loads and the second group are the rotating electrical loads.

As the word implies the static loads have no moving parts. They are primarily represented by lighting and heating equipment. Another important component of these loads are the many applications of static rectifiers. The main characteristic of static loads is the tendency for them to exhibit a resistive nature. It is true that the nature of the rectifier load depends on its control, however, there is little incentive to operate at low power factors. As a matter of fact most utilities penalize customers with low power factors very severely. Hence, in practice most rectifier loads consume little reactive power. Other static loads such as fluorescent lights may not naturally have a resistive nature but are normally compensated for the reactive requirements. This means that the power factor will be almost unity for most static power system loads.

Historically, a resistive load has been very easy to analyze. The current can be calculated simply by applying Ohms Law:

$$I = \frac{V}{R} \qquad (1 - 1)$$

I = current

V = emf

R = resistance

The power dissipated by a resistive circuit is simply:

$$P = IV \qquad (1 - 2)$$

or by substituting equation (1 - 1) in (1 - 2)

$$P = \frac{V^2}{R} \qquad (1 - 3)$$

It is seen that the power dissipated by a resistive circuit is proportional to the square of the voltage. It must also be recalled that a pure resistive circuit containing no inductive or capacitive reactive elements will have no time delay, even though this concept of a pure element is only useful academically and cannot be obtained in practice. The power consumed by a hypothetical pure resistive load will respond instantaneously in proportion to the square of the voltage.

In interconnected power systems problems are very often experienced when elements are switched. This switching can either be caused by day to day operations or protective relay action. Malfunctions in the system such as short circuits, large machine trip-outs, or faulty protective equipment may cause the whole electric system to go out of synchronism. This condition is detected by determining whether the rotor of any machine on the system moves with respect to the rotor of any other machine on the system after a disturbance without coming to a new stable angular displacement measured from the second rotor. One of the main functions of a power system engineer is to predict which disturbances will and which disturbances will not cause instability to occur in the power system and to devise methods to improve its operation. Network analyzers and elaborate computer programs are employed to study these conditions.

The assumption that all loads exhibit constant resistance characteristics has sometimes been used in stability studies. This assumption often shows a system more stable than it actually is because the power dissipated varies as the square of the voltage. This is, however, not always the case since there are situations when a load varying as the square of the voltage would give exactly the opposite effect. A typical example of this condition is the case of two power systems interconnected by one tie-line with an export of power from the first system to the second. If a fault should occur on the tie-line under these conditions the power flow will obviously be affected. If the fault is a single line-to-ground or double line-to-ground fault the transfer capability will be reduced. If a three phase short circuit should occur no power transfer is possible. In any event, even with single or two phase faults, circuit breakers are normally ganged to open all three phases simultaneously. Occasionally on modern power systems single-pole breakers are used to improve stability. When opening a ganged circuit breaker the power transfer is reduced to zero. With the reduction of power to zero, the system which was exporting power has a surplus of generating capacity and the system which was receiving power will be in a deficient position. Before any action can be taken by governors the frequency will rise in the system with surplus power and fall in the deficient one.

Along with the frequency the voltage will rise in the surplus system and drop in the other.

The existance of resistive loads on both of the systems of this example would dampen any under or overvoltages after the fault has been disconnected. As the voltage rises in the generation rich system the load would rise as the square of the voltage. This added load would reduce the voltage by increasing the voltage drop, as well as dampen the speed of the machines on the system. A stable operating point would again be reached at a higher voltage and frequency unless adjustments are made by governor action. During the period before the fault is disconnected exactly the opposite will occur, hence an ambiguity arises as to which is a more appropriate representation during the transient period.

In the deficient system a reduction in the voltage level will reduce the load thereby causing a new stable operating point as well.

Rotating Loads

In an actual system only a portion of the load exhibits resistive characteristics. The other main component of loads - the rotating constituent, does not exhibit resistive properties. These rotating loads can be further divided into synchronous motors (including convertors) and induction motors. On a steady state basis the motor loads behave essentially like constant power devices. Under transient conditions synchronous motors behave like constant power devices while the behaviour of induction motors is more complex as discussed later. The power factor will vary wildly as the voltage changes, particularly, that of small induction motors. Crary[14] says that at about 70% voltage induction motors will begin to stall. This is illustrated in figure 1.

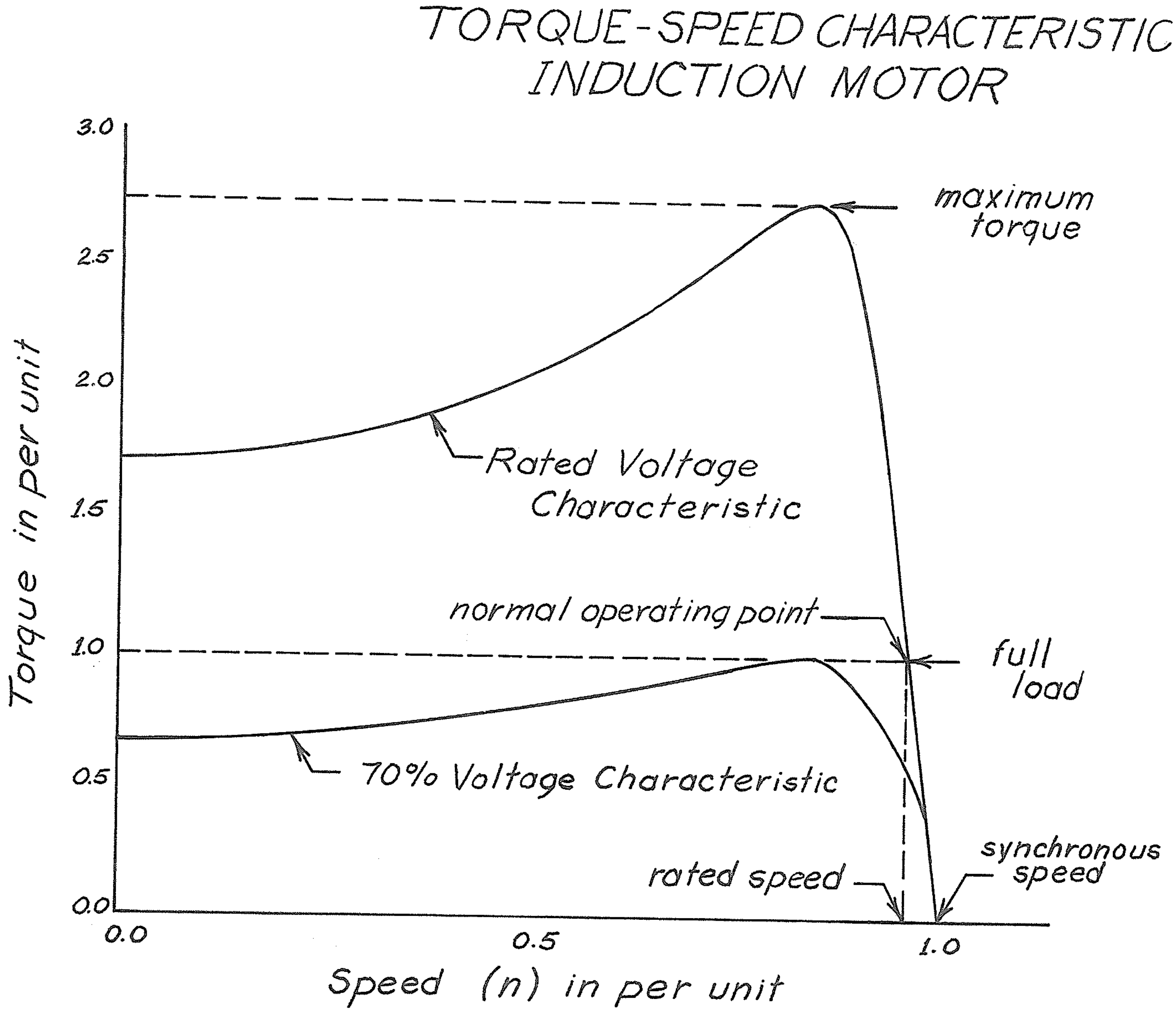


Figure 1

It can be seen in the torque - speed characteristic that when the voltage drops to 70% the operating point shifts to the left. The motor slows down, however, even worse the full load torque on the rated voltage characteristic corresponds to the maximum torque on the 70% characteristic. The motor will therefore stall.

The representation of an induction motor must be changed to its starting impedance (say $\frac{1}{6}$ x full load impedance, at a power factor of 0.2) at 70% voltage. This occurance would aggravate the condition which caused the low voltage condition in the first place. It must however be remembered that many induction motors will be equipped with undervoltage protection which would disconnect them from service. The two conditions discussed have opposite effects and tend to counteract each other. It must also be remembered that operation at 70% voltage cannot in any sense be called satisfactory and should under steady state conditions not be continued because of the danger of damage to equipment.

Two points must be raised about the discussion in the previous paragraph. Firstly, if a disturbance is so severe that voltages on a system basis have dropped to 70% it is not likely that any study would show a stable condition no matter what representation was used for the loads. Secondly, in the event a disturbance, such as a fault reduces the voltage below say 70% on a small portion of the power system any incorrect representation of this portion of the system would not effect the whole system to a great extent. This may be illustrated by a fault on a sub-system which may be about 10% of the total system. This system could be connected by a single line. If the voltage is depressed too greatly in the sub-system the supply line will likely trip out. The effect of this action on the sub-system is severe, however, the effect on the total system is not too great.

In analyzing the transient behaviour, it must be assumed that controlling voltage devices such as regulators and tapchanging transformers will have insufficient time to operate. It is even questionable whether the action of governors on generators need be represented on account of this same reason. On the other hand with modern fast excitation systems response must be taken into account due to this cause. With this assumption a brief discussion of motor performance can now be carried out. Synchronous machines as documented by Hore[23] will perform on the average over the whole period of the disturbance as constant mechanical power sinks. There are, however, relatively few synchronous motors on a system and those are usually confined to compressor service in large industries. The great bulk of rotating load will be composed of induction motors because of their simplicity and therefore capital and operating cost savings.

The analysis of the transient performance of an induction motor is somewhat more complex than that of a synchronous one.

Assuming a disturbance occurs which could be a fault the following sequence of events will likely occur. Because of the fault, voltages will drop on the system to a different extent dependent on the electrical distance from the fault. This means that the motor supply voltage will fall, however, for some two cycles, the air gap flux will be maintained by the rotor transients. The rotor transients are set up by the slight tendency to slow down caused by the reduction of torque which in turn is caused by the reduction in voltage. The air gap flux set up by the transients is in the direction of the flux caused by supply current. The supply current will therefore drop sharply. In turn, this means that the input to the motor falls. Because the mechanical load coupled to the motor remains constant the machine will decelerate giving up its stored energy. As the rotor speed falls the power input will begin to rise again due to the decay of the rotor transient and to the increasing slip. Because of the increased slip the mechanical load on the motor will be slightly less than the initial value. At fault clearance which, depending on circuit breaker speeds may vary between 5 and 10 cycles and as fast as 3 cycles under special circumstances, the power will likely be slightly lower than at prefault conditions. It must be remembered that the voltage near a fault may be depressed so low that induction motors may stall. This can also happen if a fault is permitted to linger. The motors that survive the disturbance will speed up after the fault has been cleared and when all synchronous machine oscillations have been damped out will return to the initial conditions.

A slight elaboration must be made on the induction motor performance after the fault clearance. The synchronous motors and generators on the system will oscillate. During the overswing period of a synchronous machine, induction motors near it will take increased power due to the rising frequency and also a slight increase due to increased voltage. On the other hand, the reactive power absorbed will increase greatly due to saturation at the higher voltage and partly due to the increase in frequency. It can be seen that unless a motor is represented fully including the inertia of the machine the damping effect will not be represented properly. This damping effect can be simulated by representing the motor as a constant impedance. The effect will be in the right direction, however, it will be due to the changing voltage not frequency. This means the effect is correct but the cause is wrong. Moreover, the phasing of the power oscillation will not be correct.

During the disturbance period the induction machines will slow down below the normal slip with respect to the synchronous machines but will not speed up above normal slip (unless there are machines which are unloaded or very lightly loaded). The output torque is constant so the input to the induction machine will be constant except for the small fall in speed. From the expression for torque of an induction machine in terms of voltage and slip it can be seen that the slip is inversely proportional to the square of the voltage. This is illustrated by the following equation[32]:

$$T \propto V^2 s \qquad (1 - 4)$$

or

$$s = k\frac{T}{V^2} \qquad (1 - 5)$$

also since

$$P \propto T \qquad (1 - 6)$$

$$P = kV^2 s \qquad (1 - 7)$$

If the change in speed is small it can be seen that power is approximately proportional to voltage squared and therefore approximates a constant impedance load.

Due to the effective slip the induction motor behaves not like constant impedance but like something between constant impedance and constant current. Crary[15] recommends to represent a load as a constant impedance or a constant impedance during fault and constant power after the fault.

Hore[23] suggests representing high induction motor load as constant impedance (agreeing with Crary[14]) or constant impedance during fault and constant current after fault clearing. This latter part differing somewhat from Crary[14].

It seems that either of Hore's[23] suggestions are good to represent induction motors for stability studies and the choice left to the discretion of the individual carrying out the study. One cautionary comment would be to check both representations in the event that a particular representation gives an inconclusive result.

Aluminum Pot Lines

Aluminum Pot Lines are used in the refining of metallic aluminum. These are similar to other electrolytic refining operations[30]. A chalky-white powder called Alumina (Al_2O_3), which is derived from the reddish-brown ore called bauxite is fed into a reduction furnace or "pot". In this pot it dissolves in a bath of molten cryolite to which aluminum fluoride has been added. The reduction furnace which is about ten feet wide by sixteen feet long is usually made of steel. The inner surface of this pot is lined with a paste of coke which is baked until hard and serves as the cathode. A block of carbon is suspended in the hot molten cryolite and serves as the anode. As direct current passes through this molten solution the alumina separates into liquid aluminum and oxygen. The metal drops to the bottom of the pot from where it is drained off while the oxygen bubbles off from the surface after it is produced at the anode.

Although there are no aluminum refineries in Manitoba this type of load is important to gain an insight into other rectifier types of loads. Tests carried out in Quebec in 1968 by Girdwood[22] confirmed results previously published by Kimbark[28]. Three pot lines were tested, a 100 MW ignitron rectifier line, a 40 MW ignitron line, and a 48 MW silicon rectifier line. There were no power factor correction devices connected to the lines during tests.

The test voltages were restricted to the range between 90% and 105% normal voltage in order not to disrupt production. The voltage on the pot lines was lowered suddenly by switching procedures (in this case switching out circuits supplying a portion of the reactive load).

The results obtained from these tests were plotted on a graph and compared to the results of Kimbark[28].

It was seen from the results that over the range 90% to 105% voltage the representation of aluminum pot lines as constant impedance load is quite acceptable. The error obtained will be less than 5%.

For transient stability studies it is felt that both Girdwood's[22] and Kimbark's[28] results will show the loads damping oscillations to a lesser extent before a fault is removed and a greater extent after a fault is removed because of the steady-state nature of their investigation. In the transient range (thirty cycles) and dynamic range (one to two seconds) aluminum pot lines will not have as great a damping effect as shown by the two researchers by the relatively long time constant of pot lines (several seconds).

It must also be pointed out that depending on the controls of reactifiers it is possible to change the characteristics of these loads. If a reactifier supplied an important load and it was necessary that the input to this load be constant, high speed controls could be used. These controls could simply advance the firing angle of the rectifier. In this case the power supplied to the rectifier would exhibit a constant power nature until the voltage was depressed to such an extent that the output power could not be maintained even with the rectifier firing during the whole voltage waveform.

Electric Furnaces

There are three basic types of electric furnaces[40]. These are:

1. Resistance type
2. Induction type
3. Arc type

The first of these, the resistance type exhibits characteristics similar to any other resistance and can, therefore, be represented by a constant impedance load. The induction type also exhibits a characteristic similar to a constant impedance. On the other hand, the arc furnace behaves somewhat differently. The load of an arc furnace is essentially independent of voltage and if the voltage drops the current will increase. This behaviour is classified as constant MVA. One further complication is introduced, however. If the voltage drops below about 60%, the arc cannot be maintained and the load will drop to zero. Except for the period of time that a fault is applied (5 - 10 cycles) the voltage is not likely to be low enough to cause arc extinction. If it does, the system is probably so badly split up that instability is obvious and the representation of load is only of academic interest.

Composite Loads

It is well to study and understand load characteristics on an individual basis as this helps to understand the scope of the problem. It is however, rare that a single load or a single type of load is present on the system in a concentrated area. Usually there is a wide distribution of different loads. It makes matters even more difficult that the composition of the individual loads is unknown, the operation of the loads is erratic and random and new loads of unknown magnitudes and characteristics are constantly being added.

A paper published in May, 1969, in the IEEE, Transactions of Power Apparatus and Systems by Kent, Schmus, McCrackin, and Wheeler[27] describes a very interesting and ingenious approach to the problem of load representation. The assumption is made in the paper that energy used by a particular type of load is proportional to the demand of that load when tests were carried out. They then develop a technique to relate metered energy to the composition of load. As many different substations are tested as there are different types of loads. The composition of the load is then assumed to be a function of energy used. The response of each type of load is then calculated.

CHAPTER II

GENERAL DISCUSSION OF LOAD-VOLTAGE TESTS

In a power system there are many quantities which can be measured. The two independent quantities which effect the load are:

1. Frequency (f)
2. Voltage (V)

The effects caused by changing frequency are extremely important and deserve further study. In the lab this can easily be carried out, however, on an actual system there are numerous reasons why it is not practical. Some of the main reasons are:

1. Location of Generators

The frequency can only be altered by changing the speed of the generators. Generators are normally located physically in convenient locations. These locations may be remote from loads and it may be difficult or impossible to carry out the necessary switching to isolate the loads in question on selected generators.

2. Small Variation of Frequency Permitted

Many pieces of equipment are very sensitive to variation in frequency. If the frequency is altered only a few percent the danger of equipment damage is always present. A good example of this was the recent outage in the North-Eastern part of the North American continent where generators were damaged when operating only a few percent below nominal frequency. The impedance of rotating machines as well as other equipment is reduced at lower frequences which can cause excessive currents, both fundamental and harmonic to flow.

3. Automatic Equipment Not Effective

Even though it is possible to install automatic equipment to record any disturbances and these have often been used they are not very useful for this purpose. The reason for this is that under violent disturbances many different things occur, the frequency oscillates, the voltage surges up and down, automatic protection devices operate, and electrical equipment may shut down. It is not possible to differentiate or to find out which effects were caused by what.

The two independent quantities acting on the load will cause the three dependent quantities:

1. Current (I)
2. Power (P)
3. Reactive Power (Q)

to change appropriately. It is difficult to vary voltages on a system basis, however, some locations lend themselves to this purpose.

The basic reason for this study and this report is therefore to determine the variation of current, real, and reactive power, whenever the voltage is changed. There are basically two considerations when assessing the relationship of the three quantities mentioned with that of voltage. These are:

1. Steady State
2. Transient

To measure the steady state variation it is sufficient to measure the quantities in question before and after a certain magnitude of voltage change. There is fundamentally no difficulty in measuring this relationship. The only problem is getting sufficient accuracy to determine a relationship which is meaningful.

A further word of explanation is necessary to explain the previous paragraph. During electric power system disturbances the voltage variations can be of any magnitude, anywhere from zero to one hundred percent of the supply voltage. It is entirely true that the effect of a 2% voltage variation will be different than that of a 20% to 40% voltage variation.

When permission was first obtained from Manitoba Hydro to carry out these tests it was agreed that customers on the power system were not to be inconvenienced and it was therefore also agreed that the voltage would not be varied more than 5% above or below the level found at each station.

It is not suggested in any way that a small voltage change of less than 5% affects the load in the same way as a 40% voltage variation. This is particularly so since a drastic reduction in voltage lasting more than a few cycles will invariably trigger under-voltage relays which will disconnect some loads. It is still felt, however, that a knowledge of load variation with the voltage, even if it is small, is useful. It could also be argued that it does provide some indication of how the load would respond to a large variation.

Several different ways to vary the voltage are available. These include changing the excitation of a generator supplying a radial load, varying the tap position of a regulator or an on-load tapchanger. Also available are methods such as increasing or decreasing impedance between the source and the load thereby changing the voltage drop and the switching on or off of reactive load including synchronous condensers. For steady state conditions the only methods deemed unacceptable are ones employing the switching of reactive loads. The reason is simply that the switching of reactive loads changes the load itself.

Transient Load-Voltage Variations

In transient stability studies, as well as dynamic studies, an accurate knowledge of loads will often determine the stability of borderline systems. It is important to know not only the steady state effect of varying voltage but also any difference in response during the initial half second. In the tests carried out at Manitoba Hydro stations an attempt was made to assess not only steady state variation in load caused by changes in voltage but also obtain some idea of what happens in the initial period.

In setting up the tests there were two ways available to obtain recordings of rapid changes in voltage. The first of these was the use of an oscilloscope. This device has the advantage of varying time scales. No difficulty is presented in measuring a part of a 60 cycle waveform. This would be of particular advantage in studying the initial response of load to a rapid or step change in voltage. At first it would seem that the advantages in the use of an oscilloscope would far outweigh any disadvantages. However, this was not the case.

The use of an oscilloscope does present some unique problems. It was felt that at least four quantities should be recorded. These were voltage, current, real power and reactive power. The oscilloscopes available had two traces. To record four quantities accurately at least two oscilloscopes would be required. Even with the use of two scopes a relatively complicated problem would exist with triggering. In the lab, trial and error techniques are often used to photograph the portion of a waveform of interest. It was felt on an electric power system multiple switching of circuit breakers presented opportunities for errors and for possible customer outages. It was possible to obtain a storage oscilloscope, however, this did not present any advantages.

In the end it was decided to use a galvanometer type ultraviolet recorder. It was felt that the response time was very satisfactory as an instrument of this type will record accurately frequencies up to about 600 hertz. Power system characteristics change more or less as step functions. These are caused by initiation of a disturbance, the switching of equipment protected by relays due to the isolation of defective components, and finally secondary switching caused by overloading or instability. Each of these conditions normally lasts for three to five cycles since this corresponds to circuit breaker opening times. Since the length of the steps of a disturbance are generally in the 5 cycle or 80 millisecond range a recorder capable of measuring changes in the 1 to 2 millisecond range is adequate.

Another advantage of the ultraviolet recorder is the many channels available for recording. Only four quantities were measured, however, up to 24 different quantities could be measured.

Ultraviolet Recorder

The ultraviolet recorder chosen for the tests required an input of 150 millivolts or less. Because all metering circuits in Manitoba Hydro stations are normally rated at 5 amps and 120 volts, transducers were required for all quantities recorded. The transducers converted voltages, currents, real and reactive power into milliampere quantities. These currents flowed through resistors as shown in figure 8. A millivolt quantity was provided to the recorder. Using this type of set-up, recordings were taken at a number of Manitoba Hydro stations. After reviewing and analyzing the results it was felt that the results were not accurate enough and therefore totally unacceptable. The problem with these first tests was that a full-scale deflection corresponded to a nominal quantity, lets say 120 volts or 500 watts. The change in voltage had to be limited to 5% and in most cases was about 2%. This meant that with a 1% accuracy built into a recorder the changes in the quantities were in the same order of magnitude as the possible error. It was also exceedingly difficult to measure changes of one or two millimeters with any degree of accuracy.

Bias Circuits

To overcome the problems in accuracy and to be able to measure changes easily it was decided to use a bias circuit to bias each of the millivolt quantities representing voltage, current, real and reactive power to zero. This meant that before any change was made to the voltage, all quantities would be reading zero. This also meant that only the change in each quantity would be measured. Because these quantities were small they were amplified with four galvanometer drive amplifiers. The gain could be turned up on the amplifiers until a reasonable change in each quantity was recorded.

D.C. Power Supplies

It was found that any D.C. power supply operating from the A.C. source at each station would experience the same voltage change as the load and therefore would be unacceptable for the purpose intended. Dry cells were considered, however, it was felt the drain across a voltage dividing resistor would change the output voltage of a dry cell.

A solution to the D.C. power supplies for the biasing circuits would be to use high speed electronic regulated power supplies. These were not available. However, one high speed electronic regulator was avilable. It was therefore decided to improvise and use this A.C. regulator to supply four A.C./D.C. adapters which were designed to operate transistor radios. These units had the advantage of being very cheap and locally available. This set-up for biasing the output of the transducers proved very effective and without their use it is unlikely that any meaningful results could have been obtained.

Filter Circuits

The transducers are essentially full-wave rectifiers that behave like a current source. The D.C. current of the output is not a true D.C. but has a fair amount of ripple caused by harmonics. The response time of the transducer is excellent being in the range of 3 milliseconds for most units. Because of the biasing technique used and the amplification of the output, the harmonics found in the output were also amplified. To overcome this situation manufacturers produce some transducers with built-in filters to remove unwanted harmonics. The filters are effective in removing harmonics but they in turn increase the response time. Manufacturers have decided that a good compromise between unwanted harmonics and poor response was to employ filters that increase the response time to about 300 milliseconds which is still reasonable and by doing this most of the harmonics are suppressed.

In the tests carried out, the only transducers available were units which were unfiltered having a response time of about 3 milliseconds.

It was decided to build filters which would increase the response time to not more than about 300 milliseconds.

It was found in the tests that the remaining harmonics which were present were not objectionable.

As a further refinement and improvement to accuracy it was decided to take response characteristic curves for step changes. These curves could then be used to predict what would have happened if there was no time delay. These response curves are shown in Appendix C. From the curves it seems that all the delay is in the recording equipment and the load essentially responds as a step function to voltage.

Reproduction of Ultraviolet Traces

In compiling the results of this study it was felt copies of the ultraviolet traces were required for references purposes. With this in mind, methods of reproducing these traces were investigated and sampled. All the common methods of reproduction such as photocopying, xerography, and offset, were tried. There was no method that proved satisfactory.

Three problems were encountered when copies were being made. The first of these problems was light exposure. The ultraviolet process inherently uses photosensitive paper. Light turns the paper dark. It is possible to use stabilizers on the paper to make the traces "permanent". It was however, found that the paper still turns dark. Any reproduction method which uses intense light very drastically increases the darkening process. After two or three such copies are made the original recording becomes almost useless for any further study.

A second, somewhat related problem, is the storage of recordings for relatively long periods of time. The traces will disappear eventually. If permanancy is required then some form of copying is needed.

The third problem encountered in making copies was the lack of contrast in the ultraviolet recording. Any copy made was so poor it was not considered useable.

Because of the problems encountered in making copies the only solution was to manually trace the recordings with India ink. This method proved satisfactory from the point of making copies. It nevertheless proved to be a very time consuming and tedious method that required several weeks of work.

Accuracy of Results

In any set of experiments the question of correctness and precision of results always comes up. The instruments used were well suited with a guaranteed accuracy of $\pm\frac{1}{2}$ of 1 percent at rated value. The readings were taken normally at half deflection or less which would tend to decrease the accuracy. Even so, the results should be more accurate than normal data such as loads used in modelling a power system. Very often it is quite satisfactory to have an accuracy of ±5% or even ±10% for such quantities as loads.

From a perusal of the results of the tests it can be seen that they seem to be at least basically consistant if not precise. It must be pointed out that the loads varied a great deal during the tests due to basic load variations. Once or twice the traces on the charts went off scale. This means that judgement had to be used in assessing the values of the before and after quantities.

It must also be pointed out that when errors occur it would be expected that just as many high readings as low would be found. In the results the findings were often contrary to what would be expected by representing loads as constant power, current, or impedance. As a rule the loads were much more sensitive to voltage changes than even constant impedance representation.

Use of Data in Stability Studies

There are two main stability studies which are carried out in power system investigations. These are:

1. Transient Stability Studies
2. Dynamic Stability Studies

The first of these, the transient stability is characterized by the "first swing" criterion. That is if the first swing of a machine or system turns around then the system is said to be stable. The swing of the machine or system is generally initiated by a major disturbance such as a fault. Any input into control devices on the power system are large because of the large changes on the system. Sometimes this is referred to as "large signal" stability studies. The transient period is about twenty to thirty cycles.

The second of these, the dynamic stability studies have become of much more importance in recent times because of the general interconnection of power systems and interaction of many machines and systems. After the initial transient period control systems start to react to the initial disturbance to help the system stay in synchronism. Sometimes, these control systems can cause oscillations or hunting between systems. If these oscillations increase in magnitude instability will result. The input to the control systems after the initial disturbance will be caused by swings which are not as severe as the original disturbance. Hence, sometimes the term "small signal" stability studies is used.

In obtaining data for stability studies a characteristic such as shown in figure 2 is often realized.

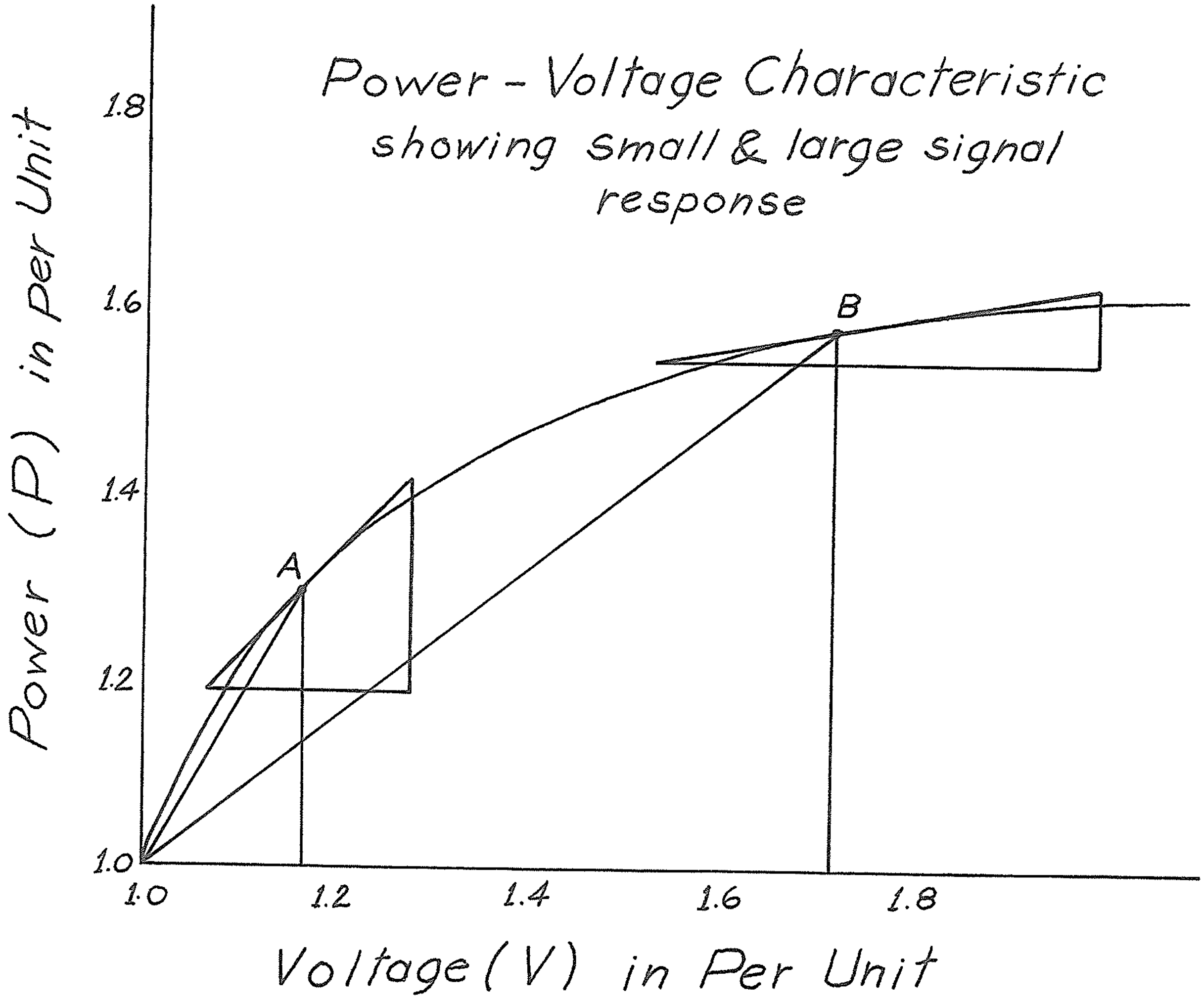


Figure 2

As can be seen the characteristic is non-linear. The triangle drawn from the origin to point A depicts the type of response required for a small change in voltage. The slope of the curve is steep. The slope of the triangle from the origin to point B shows a greatly different type of response required for a large change. The two small triangles at point A and point B show the slope of the characteristic at these two points or the power as a linear function of voltage at these specific points.

Because of the non-linearity inherent in power systems often compromises have to be made in choosing control systems. In practice it is often necessary to divide a response curve into two or more sections with different types of control for each section. This type of control is illustrated in figure 3.

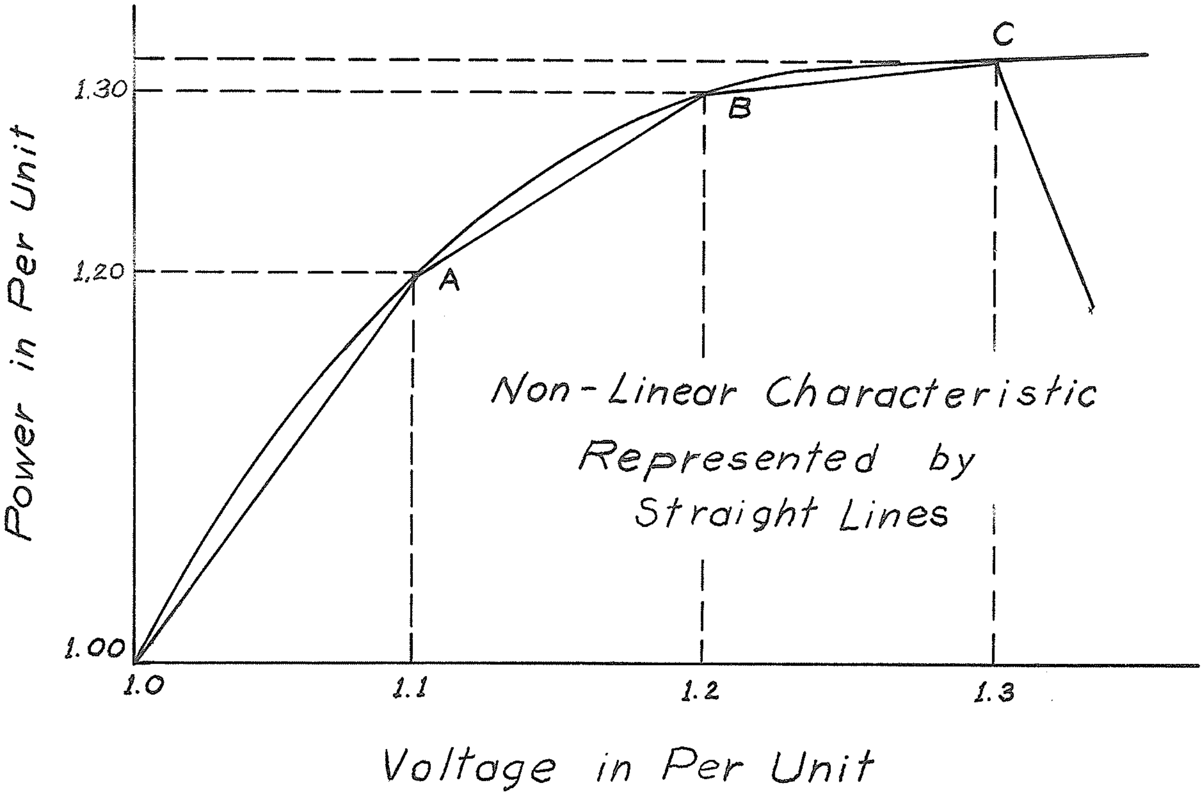


Figure 3

For the section between the nominal value and 1.1 p.u. voltage the response can be linear and represented as a constant impedance. Between point A and point B (1.1 to 1.2 p.u.) the response begins to saturate and can be represented by a straight line having a different slope. This portion of the curve could approximate a constant current behaviour.

After point B on the characteristic the curve flattens out much more and becomes almost horizontal. This portion can be approximated by a horizontal straight line which is another way of saying that power over the range of 1.2 to 1.3 p.u. voltage is constant power. Lastly when the voltage increases beyond about 1.3 p.u. the characteristic starts dropping rapidly. This is intended to indicate overvoltage relay action which is disconnecting loads. This portion can also be represented by a straight line, however, by now it is evident that conditions are grossly unacceptable as far as voltages are concerned and the system is likely unstable. Similarly a characteristic can be drawn for voltage dropping with several segments approximated by straight lines and finally the load dropping off when disconnected by undervoltage relays.

CHAPTER III

GENERAL DISCUSSION OF RESULTS

In analyzing the results it seemed reasonable to express the three quantities - current, real power and reactive power as a function of the voltage raised to an appropriate power.

$$I = k_I V^{x_I} \qquad (3 - 1)$$

$$P = k_P V^{x_P} \qquad (3 - 2)$$

$$Q = k_Q V^{x_Q} \qquad (3 - 3)$$

It is apparent that with the three common types of loads, the exponents of the voltage would be as listed below:

Type of Load	x_I	x_P	x_Q
Constant Current	0	1	1
Constant Power	-1	0	0
Constant Impedance	1	2	2

Not only can the loads be represented by the three methods listed but real and reactive parts of the loads can be represented differently. For example, the real power component can be constant impedance and the reactive component constant current or any other combination.

It can be seen from the tabulation of types of loads on the preceeding page that the exponents x_I, x_P, and x_Q, vary between -1 and 2 for all conceivable combinations of loads. From this it would indicate that exponents greater than 2 are not possible.

In all the 67 test cases carried out, on 9 independent loads there were no negative exponents found as can be seen in Table 1. This would indicate that constant power loads are in the minority. This could easily be believed since a great majority of the loads tested were commercial, domestic, and farm with large heating and lighting components.

The heating and lighting component was not in the majority at the Rosenfeld Station, since the majority of the load was induction motors used at the Interprovincial Pipeline Pumping Station at Gretna.

Not only at Rosenfeld, but at all locations it was found that the exponents as calculated by equations (3 - 1, 3 - 2, and 3 - 3) often were larger than two. This at first seemed impossible and unacceptable. However, on reviewing research on this topic and searching published and unpublished work it was found that other investigators have found similar results. In the case of the reactive power the large exponents are likely caused by the saturation of transformer iron, a point that will be discussed further. The real power on the other hand can be explained partially by the time interval that the major change in load occurred in. As can be seen by examining the traces the response curve lasts only about 200 - 300 milliseconds. This fact is borne out by the timing trace at the extreme left hand side of the chart. Energy stored in electric or magnetic fields can have time constants of several seconds. The transient swing of a system would normally be over before these secondary effects would occur. The natural load variation on the system would tend to mask these relatively longer term effects.

It was also desired to test the system response to voltage variations at key major stations on the Manitoba Hydro system. These stations such as the Brandon 17th Street East Station supply large areas such as the City of Brandon or the South-West area of Manitoba. By this means it was hoped to obtain the response of an equivalent load which represents the total load supplied from a particular station. By doing this it is inevitable that the effect of transmission systems and transformers as well as control equipment was being recorded as well as the load.

In the case of the Brandon 66 kV area, the charts, a sample of which is included in Appendix C shows that the voltage change caused by dropping a transformer bank was minimal. The dependent quantities on the other hand vary out of all proportion to the change. This effect seems to be caused by the maintenance of almost constant voltage by relatively large synchronous condensers at Boissevain.

It must also be pointed out at this time that the three dependent quantities varying as a power greater than two when related to the voltage is not new. In Appendix G a letter is included for reference. This letter, written from Mr. W. J. Tishinski to Mr. C. J. Goodwin of Manitoba Hydro dated April 15, 1968 describes tests carried out on the Manitoba Hydro system in 1968. The letter describes currents and powers varying as the fifth and third powers of the voltage. At that time it was felt that an error must have been made in measurement or instrumentation. The tests in 1968 measured actual quantities so it was relatively difficult to measure the change in a quantity. In the present tests the instruments recorded only the change in a quantity. Measuring a change in quantity in this fashion is inherently more accurate by at least two orders of magnitude because the change in a quantity is in the order of 1% to 2% of the absolute quantity. The change in quantity is then amplified to obtain a reasonable deflection on the recorder.

In the section on accuracy a discussion is made on errors that can be expected. The equipment used besides the transducers is basically $\frac{1}{2}$ of 1% accurate. In any event taking any unforeseen continguency into account the accuracy should be within 5% or at worst 10%. Accuracy is therefore not a consideration when evaluating the results.

In April, 1968 a paper was given at the CEA Toronto meeting entitled "System Stability Performance as Affected by Load Representation for Computer Studies and Field Tests"[18]. The two authors, C. R. Desrosiers and J. C. Roy describe tests taken on the Hydro Quebec system from which they suggest that in the transient region the power varies as the square of the voltage and the reactive power as the cube of the voltage.

For the dynamic region they suggest that real power varies as the first power and the reactive power as the square of the voltage.

In any event this paper confirms that variation of load greater than the second power of the voltage has been experienced by other investigators.

After the current tests on the Manitoba Hydro system were conducted and were being analyzed it was brought to the author's attention that two papers were available on this topic. The first was entitled, "Demand Responses to Changes of Voltages - Report on South Wales System Tests" by G. Shackshaft, O. C. Symons and J. G. Hadwich[34]. In this paper the authors describe the results of tests taken in Wales which were basically similar to the ones carried out in Manitoba. Except for one case the real power did not vary to a greater degree than the second power with respect to the voltage. However, the reactive power varied to as high as the 40th power, but normally it averaged between the 4th and 27th power. The three authors explain this behaviour by suggesting that the portion of the reactive power required to excite both power and distribution transformers increases very much more rapidly than the load portion of reactive power. This in turn causing a large change in reactive power whenever the voltage changes, particularly when the load is light and the reactive power is predominantly used for exciting transformers.

The above observation can be deduced without formal proof by the fact that transformers, particularly modern power and distribution transformers are being operated farther along the non-linear portion of the characteristic as shown in figure 4.

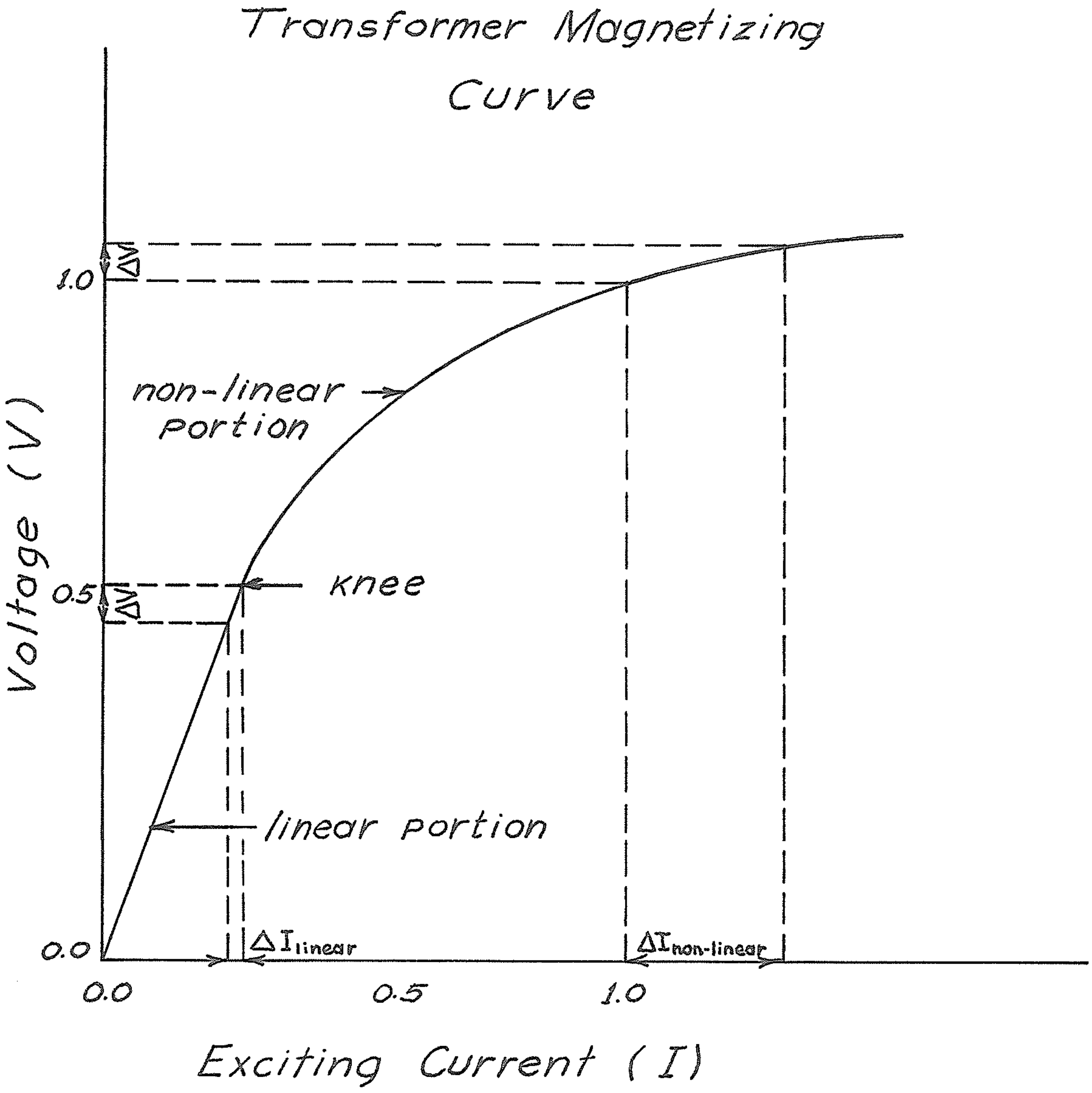


Figure 4

It can be seen that the same voltage change in the non-linear portion of the magnetizing curve will cause a much greater current and hence reactive load than if the transformer was operating along the linear portion of the curve. The decision to operate transformers in the non-linear region of their magnetizing curve is predicated by a desire to reduce costs and the physical size of transformers. This in turn leads to the reduction of the iron in each unit.

From the study of diversity on the Manitoba system in the past it was found that often the transformer capacity installed can be as great as three times the load. If it is assumed that the magnetizing component of the kVA demand is about 1½% of the transformer rating it is evident that the reactive requirements for transformer magnetization would be in the 4½% of load area.

The Manitoba Hydro load is highly compensated especially in rural areas. As a matter of fact leading power factors are not uncommon. Needless to say reactive load requirements at most bulk supply points are small, often 10% of the real power or less. The magnetizing component therefore becomes an important component in the total reactive supply. At times it is possible that the reactive supply is predominantly for transformer magnetization. It therefore appears that in Manitoba as in Wales that the iron saturation contributes greatly to the very high reactive load response to voltage changes.

The second of the two papers was prepared by the

Computer Analysis of Power Systems Working Group of the Computer and Analytical Methods Subcommittee - Power System Engineering Committee, IEEE[31]. In tests which were conducted at Barrie the reactive power varied as high as the 4th power of the voltage.

The authors of this second paper state a comment about response times of loads — "In general it is valid to conclude that residential loads have negligible inertia time constants". This corresponds to the results found in Manitoba where no real difference in results could be detected between actual step changes imposed on the recording equipment and the response of the loads as recorded. This point is illustrated in Appendix C where the response curves taken in the shop have almost exactly the same time constant as the load curves taken in the field. The response curves in the shop were taken by shorting out current transformers. The conclusion that can be derived from this comparison is that load response is almost a step function when the voltage change is a step function.

It is evident from the tests carried out on the Manitoba Hydro system as well as a number of papers published in the literature that reactive power can vary very greatly with the voltage. In the literature at least one case was discovered with the reactive power varying as the fortieth power. On the Manitoba Hydro system in one case the reactive power varied to a greater power than one hundred. This particular case seems so extreme partly because of the large synchronous condensers connected at the specific location where this was recorded. Disregarding this specific location reactive power varying as the 10th power of the voltage was not uncommon.

A point which must be reiterated is that data on the Manitoba Hydro system was required for transient conditions. With this in mind readings were taken to reflect conditions during the 20 - 30 cycle period after a disturbance. If bona fide steady state readings were taken the variation of real, reactive power, and current would not have been as great, however the variations would still be far in excess of the maximum theoretical values which would be given by a constant impedance representation.

An extremely important finding in the tests carried out was that the real, reactive power and current not only were a function of voltage but were also a function of the change in voltage. This statement has to be constrained by the fact that voltage changes were small.

Because there are no means of varying the voltage in some systematic fashion only voltage changes of a fixed amount determined by bank impedances were possible. It can be seen from the data and the following two curves that as the voltage change increases in magnitude the other changes decrease as a percentage of the starting values. It would seem from this observation that in a power system the loads provide a large damping effect for very small voltage changes. As the voltage variations increase the damping diminishes. It is anticipated that there is a limit to the decrease in the damping of the loads. This limit would be very important to the power system if any means existed to accurately measure it.

In a power system it would be important to obtain information on the damping effect of loads during large voltage variations because an assumption made based on disturbances causing small voltage variations could be inaccurate for large changes. Since small disturbances are normally associated with small voltage changes which would not represent critical situations for the system the representation of loads during such conditions would be only of academic interest. The accuracy of load representation under large voltage variations is of utmost importance because these are the conditions under which instability occurs.

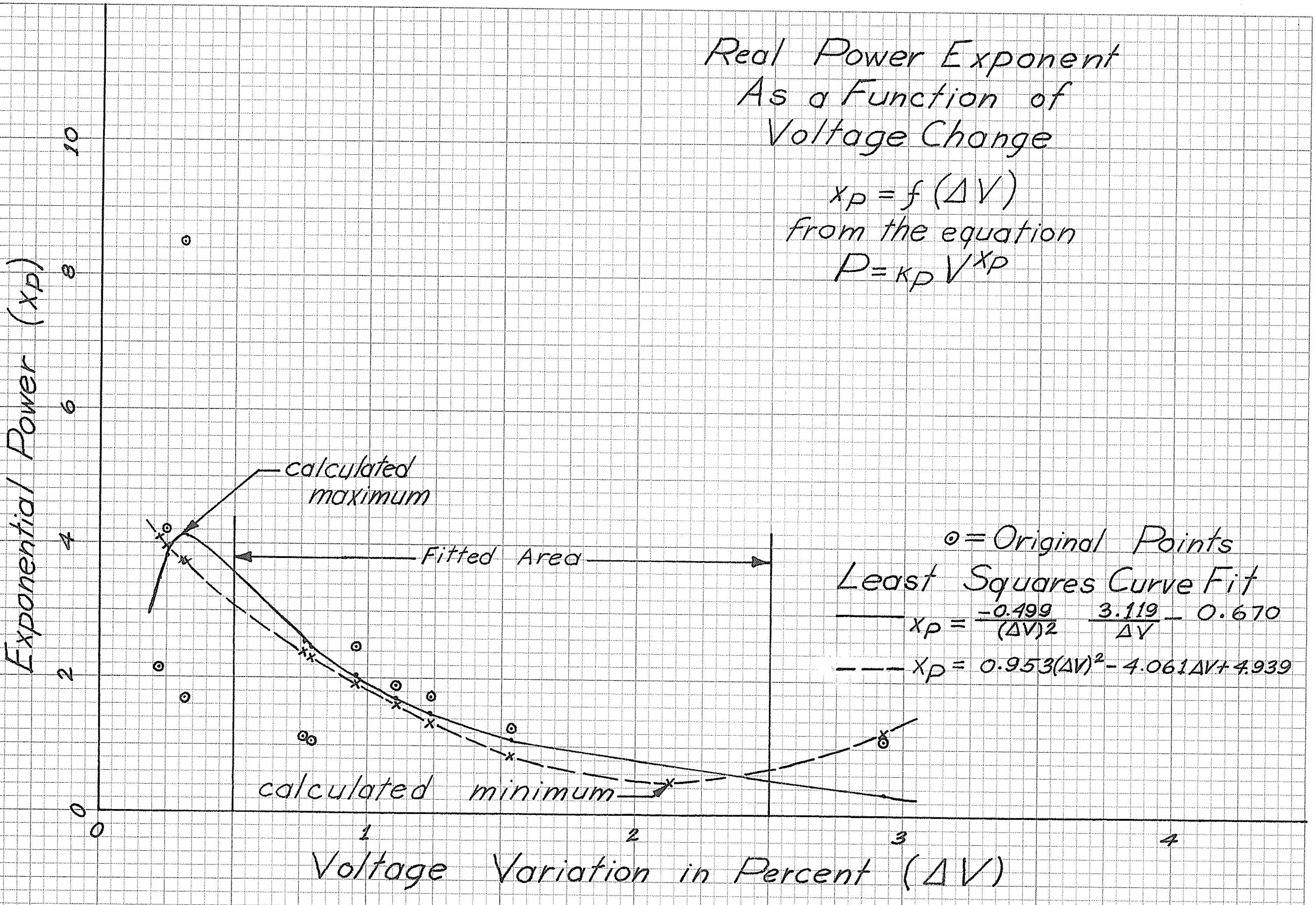
At present there are no means of varying the voltage more than a few percent about nominal. Even if it were possible to rapidly vary the voltage by a large amount it is questionable whether this could be tolerated without severe customer relations problems.

One solution to the obtaining of data under large voltage excursions is to install automatic recording equipment which is triggered by disturbances on the system. This at first seems like the optimum solution. On more detailed investigation it is found that disturbances on a power system are caused by phenomena such as faults and equipment disconnection. Invariably whenever the voltage is increased or decreased the frequency also increases or decreases. There does not seem to be any means to differentiate between the voltage and the frequency effects. This is the reason why automatic equipment has not been installed for this purpose.

Two graphs were produced showing the type of function that the real and reactive power are of the voltage. All the tests were treated as if they were readings on the same load. Because of some variation between readings caused by the same equipment being switched out average values for each group of tests were used. Therefore some stations will have more than one value for voltage variation and load variation. The average values plotted on the graphs are tabulated in Table 1. These graphs are shown in figures 5 and 6.

After reviewing the data it was felt that possibly some more sophisticated approach should be used for curve fitting. A computer program employing the least squares method was used to fit two different curves both for the real and reactive power. The problem with curve fitting is that the type of function depicted has to be chosen first and then appropriate constants are calculated. The procedure does not establish the function. After eliminating data from Brandon which were out of line with the rest of the data, two functions were chosen for curve fitting. These were of the following nature:

$$y = \frac{A}{x^2} + \frac{B}{x} + C \qquad (3 - 4)$$



Real Power Exponent As a Function of Voltage Change

$x_p = f(\Delta V)$ from the equation $P = \kappa_p V^{x_p}$

Figure 5

December 1973 V.J.S.

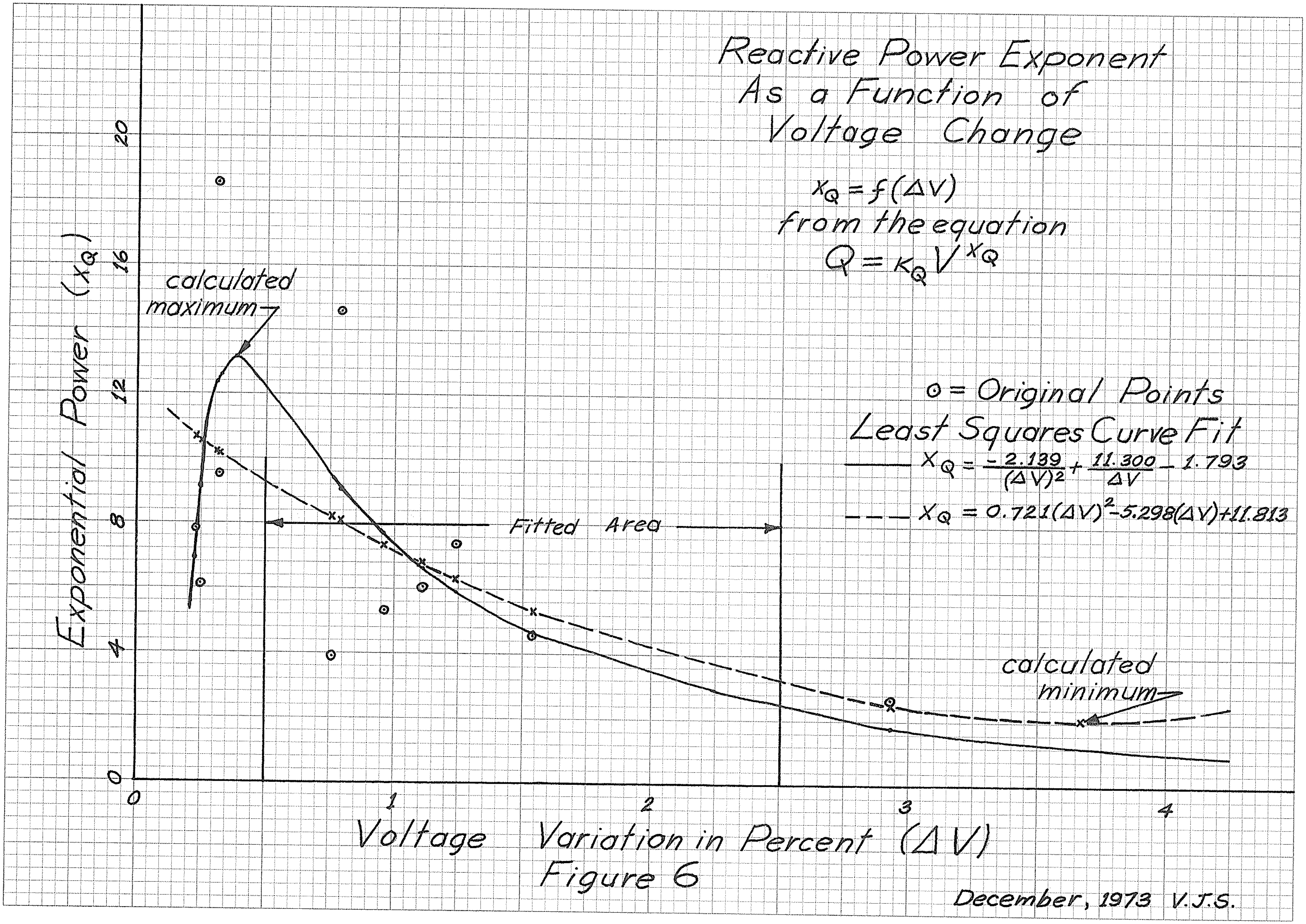


Figure 6

December, 1973 V.J.S.

$$y = Ax^2 + Bx + C \qquad (3 - 5)$$

Both of these curves fit the data quite adequately between about 0.5% to 2.5% voltage change. Both curves illustrate a downward trend in the response of the real and reactive power as the change in voltage increases. Without extrapolating the data past the 2.5% voltage change the data would indicate that the real power is a function of the voltage and the reactive power is a function of the voltage to the third power. It is felt that the real power is probably a function of the voltage to the 0.8 power with larger voltage changes, however, this cannot be proven by the data available.

The response of the real and reactive power could be approximated by representing the real power as constant current and the reactive power as constant impedance. It would seem that the above relation would be valid until the voltage dropped to the point where motors would stall, arcs would extinguish, loads would be disconnected by relays, etc.

Procedures in Obtaining Data and Sample Calculation

In Chapter II a discussion was given on the time delay present in the transducer circuit. Because this time delay of about 300 milliseconds is caused primarily by the filtering circuits the ultraviolet traces were used to obtain readings in the 300 to 350 millisecond range. This is shown in figure 7. Without this time delay of the transducer circuits the response of the load would be almost a step function.

The average value in the 300 - 350 millisecond area for the varying quantity was used. In the example the change in voltage (ΔV) was 3 volts. The voltage before the commencement of the test was 120 volts.

Therefore the percent change was:

$$\%\Delta V = \frac{\Delta V}{V} \times 100 = \frac{3}{120} \times 100 = 2.5\% \qquad (3 - 6)$$

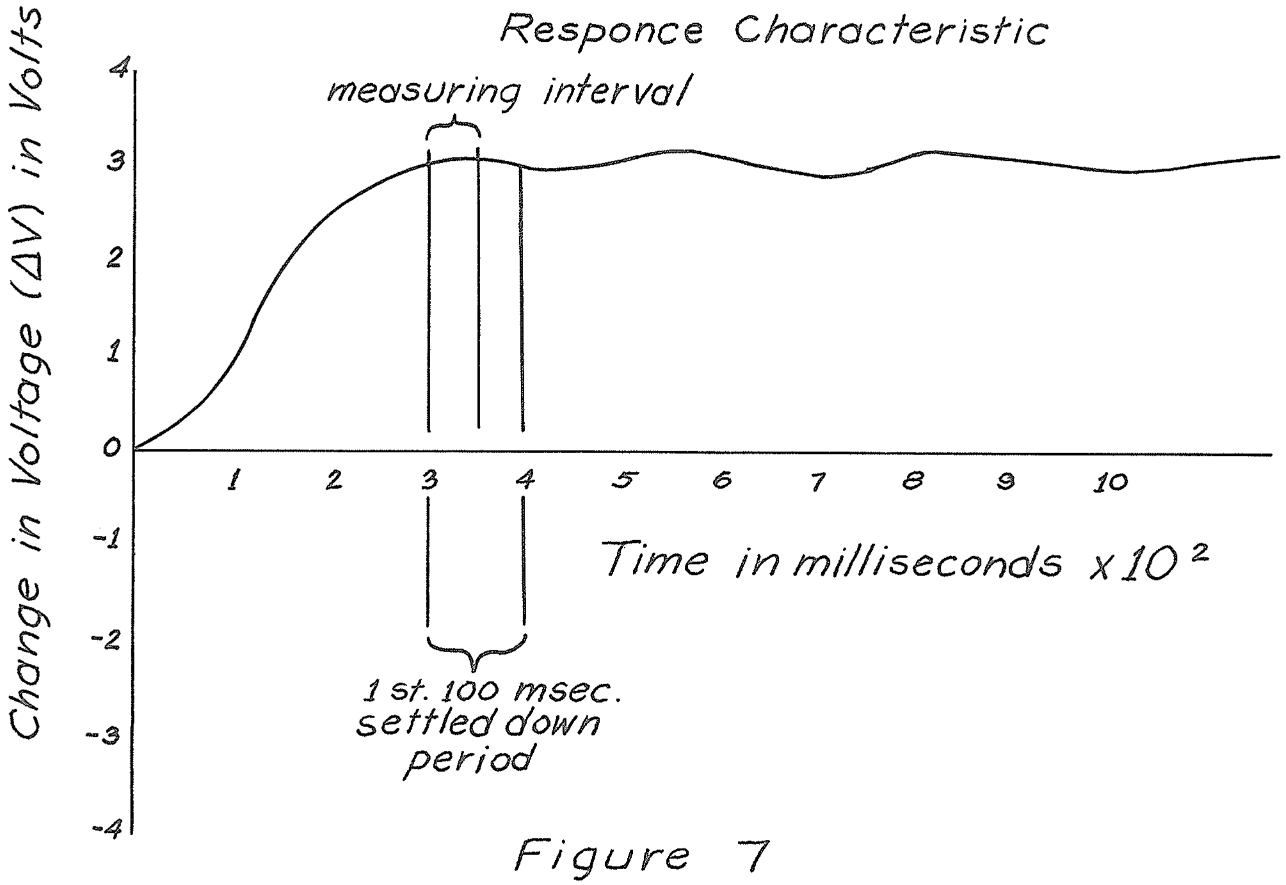


Figure 7

In a similar fashion the percent changes in the other quantities were obtained.

In determining what function each of the dependent quantities were of the voltage the following manipulations were carried out:

Initial Conditions -

$$P_0 = k_P V_0^{x_P} \qquad (3 - 7)$$

where P_0 = power before voltage change

k_P = constant relating power to voltage

V_0 = voltage before change

x_P = unknown exponent relating power to voltage

Final Conditions -

$$P_F = k_P V_F^{x_P} \qquad (3 - 8)$$

where P_F = power after voltage change

k_P = constant relating power to voltage

V_F = voltage after change

x_P = unknown exponent relating power to voltage

From the above a ratio can be established:

$$\frac{P_0}{P_F} = \frac{k_P V_0^{x_P}}{k_P V_F^{x_P}} \qquad (3 - 9)$$

By cancelling and cross-multiplying the following is obtained:

$$P_0 V_F^{x_P} = P_F V_0^{x_P} \qquad (3 - 10)$$

Using the per unit system and defining initial conditions as:

$$P_0 = V_0 = 1.0 \text{ p.u.} \tag{3 - 11}$$

The following expression is obtained:

$$V_F^{x_P} = P_F \tag{3 - 12}$$

Taking the natural logarithm of both sides of the equation the following expression is obtained:

$$x_P \ln V_F = \ln P_F \tag{3 - 13}$$

and finally,

$$x_P = \frac{\ln P_F}{\ln V_F} \tag{3 - 14}$$

This equation solves for the unknown exponent x_P.

The Effect of Time on the Effect of Voltage Change

It was felt that possibly time had an effect on the relationship of current, real and reactive power. This type of relationship could be expressed by the following expressions:

$$I = k_I V^{x_I(t)} \tag{3 - 15}$$

$$P = k_P V^{x_P(t)} \tag{3 - 16}$$

$$Q = k_Q V^{x_Q(t)} \tag{3 - 17}$$

The effect of time could be expected to show up in two places. The first is illustrated by the curved portion of the curves in Appendix C. This effect would have a short time constant. A longer term effect would be a gradual change in a dependent quantity over several or many seconds. Another way of saying this would be that this second effect has a long time constant.

As can be seen by the response curves taken in the shop and comparing these to the curves taken in the field, the short range effects are almost instantaneous as almost all the time delay is in the metering circuitry. On the other hand any longer range slower changes to the current, real and reactive power are completely hidden by the normal random load changes. Even though no doubt time has an effect this effect would be of secondary importance.

CHAPTER IV

SPECIFIC DISCUSSION OF RESULTS

Kirkfield Station

The results of the rapid variation of voltages at the Kirkfield Station are shown in table 1. The voltage was reduced and raised seven times from the normal value. Since there are only two transformers of identical design only one magnitude of voltage change was possible by dropping transformer banks or in other words switching one of two parallel units out, increasing the impedance and voltage drop, therefore changing the voltage.

From the results it can be seen that the voltage was lowered by approximately three percent. The actual cases ranged from a reduction of 2.82% to 3.22%. The voltage was increased by approximately 3 percent as well. This figure varied from 2.83% to 2.92%.

Again from table 1 it can be seen that the current varied from a low of 2.16% to a high of 2.52% in the positive direction and 2.10% to 2.48% in the negative direction for for seven tests. The real power varied somewhat more, ranging from a maximum of 3.64% in the negative direction to 3.48% in the positive direction.

The variation of the reactive power was much more sensitive to the change in voltage. This can be seen by the change in reactive power varying from -9.25% to 8.25%.

Because the magnitude in voltage change caused by bank dropping was fixed, there was not any way to produce a series of voltage changes of varying magnitudes at the Kirkfield Station. There is some indication that the magnitude of the voltage change itself effects the degree of the change in load.

Also in table 1 can be seen that from the tests taken at this station the real power varied as the voltage to the 1.12 power on the average. The reactive power on the other hand varied as the voltage to the 2.64 power. With these two observations in mind it could be argued that a good representation of loads at the Kirkfield Station would be constant current for the real component and constant impedance for the reactive component.

St. Vital Station

The results of the tests taken at the St. Vital Station are shown in table 1 and samples of typical traces of the load variation in Appendix C.

It can be seen from table 1 that the change in voltage was in the order of 1%. This change in voltage caused a change in current varying from a low of 1.63% in the positive direction to a high of 2.41% in the negative direction. The real power change caused by the voltage change varied from a low of 2.07% in the positive direction to a high of 2.75% in the same direction. The average being in the 2.35% area.

Again as in the case of the Kirkfield Station the reactive power was much more sensitive to voltage variations than real power. The range being from a low of 3.29% in the positive direction to a high of 7.47% also in the positive direction. The average being 5.17%.

Table 1 also shows the power of the voltage, that the current, the real and reactive power are functions of. It can be seen that in the case of the real power the range was between 1.94 and 2.87. The average would not be far from the behaviour associated with constant impedance. Again it can be seen from the table that the reactive component varies a great deal more than the real power. The range of variations being 3.42 to 7.46 with an average of 5.31. The current exponent varied between the range of 1.71 to 2.58 with an average of 2.19.

A very interesting phenomenon can be seen in the copies of the traces of real and reactive power and current. Very large swings of a low frequency were experienced whenever the voltage was raised (not lowered) particularly for the reactive power. This could not at first be explained and it was felt that some malfunction in recording equipment was causing these swings. The equipment tested out accurately as well as no similar swings of such a magnitude were experienced anywhere else in the tests taken. It was believed that the low frequency oscillation which died out after a number of cycles was caused by the tuning of the transformers and 66 kV St. Vital System with the transformers and large capacitor bank (8.4 MVAR) on the 24 kV system. This could easily have been proven or disproven at the time of the tests if it had been suspected at the time. Since a similar occurance did not happen anywhere else it was not felt important to reorganize the tests again. The low frequency oscillations were very similar to those that sometimes are set up between neighbouring electric systems. The oscillation between electric systems do not dampen out as quickly. Their cause is also different — being the changing rotor angles of the machines on the two systems. In the case of the St. Vital System there is a relatively large transformer in series with a capacitor in parallel with the rest of the system. When the transformer which was switched out was switched back in, the charged capacitor discharged into the inductive impedance of the transformer. The magnitude of the swing depends on when during the voltage sine wave the switch is closed. In a perfect lossless system the stored energy would alternately swing from the capacitor to reactor then back to the capacitor indefinitely. In the actual case because of the effect of resistance present the oscillation dies out quickly.

Parkdale Station

Before the tests were undertaken it was felt that the most useful tests would be taken at Parkdale. This was because of the switching arrangement at this station. Two radial 33 kV systems are supplied by two transformers each. In turn each of the 33 kV supplies are regulated by two voltage regulators. It was hoped to parallel the two regulated supplies and raise the tap position on one regulator while lowering the tap of the other. It was also hoped to obtain a difference in tap of at least five and preferably ten percent. Calculations were done to determine the "circulating power" which was expected. Under medium loads it was predicted that a current approaching 200% that of the rating of regulators would flow. As it turned out the day of the tests was cold with a heavy system load. It was estimated that the load on the regulators with dissimilar taps would be 250% of rating or higher. Because of this and the fact that each of the regulators had to be repaired the previous summer, clearance could not be obtained from the System Dispatchers for the planned tests with the planned voltage differential. Instead it was agreed to drop transformer banks.

Because of the relatively large size (4 x 15/20 MVA) of the transformers and the relatively small load (13.0 MVA) the voltage changes caused by the bank dropping were small. Most of the changes were of a magnitude of 0.25% to 0.30 percent. It may be that a voltage variation of 0.25% may have no relationship to that of a voltage variation of 10%. The findings are nonetheless reported as findings of the study, keeping in mind the limitations of the data. The accuracy of the test equipment was $\pm\frac{1}{2}$ of 1%. This, however is for rated conditions. It is estimated that for very small deflections the accuracy could be ±30%.

Table 1 shows that a 0.25% voltage variation causes the real power to vary roughly 1.00%. As found in all previous cases the reactive power is more sensitive to voltage variations and changes by 1.53% on the average. The current variation did not match either of the above rates changing only about 0.77%.

Also in table 1 the exponents which the three dependent quantities are a function of the voltage of are listed. The real power exponent varied between 2.21 and 6.98 with an average of 4.21. The average of the current exponent was 3.11. It can again be seen that the reactive exponent is larger averaging 6.13. Very roughly it can be said that the current and real power exponents are of the same magnitude. The reactive power has little influence because of its small size at Parkdale.

Rosenfeld Station

The Rosenfeld Station supplied a predominantly large motor load. In observing the traces of the tests taken at this station it can be seen that a slight oscillation is set up by a voltage variation. This oscillation was caused by the nature of the load — the reaction of large rotating masses to rapid changes in voltage and therefore torque and load.

The transformers used at Rosenfeld were identical to the units at Parkdale. Again it could be predicted that voltage variations would be small. As it turned out the actual variations were in the order of 0.25 to 0.45%. This was disappointingly small, however, no other means for voltage variations are possible at the present time at this station.

The voltage change at this station caused a current change in the order of 0.70% while the real and reactive power changed a great deal more. The real power varying between a low of 1.26% in the positive direction and to a high of 4.59% in the negative direction and the reactive power being a low of 5.11 and a high of 6.79%.

Table 1 also shows which power the dependent quantities are functions of the voltage. The range for the current is between 1.81 and 2.87. The real power changed between 5.10 and 10.45 with an average of 8.56. The reactive variation, again larger than the others was between 15.14 and 23.94.

Brandon 17th Street East Station

The Brandon Station proved to be the most interesting station for two different reasons. The first of these was the fact that two distinct loads exist at this station which can be tested separately. It was possible to test two different loads from one set-up. The second situation which caused the Brandon Station to be of such interest was the effect of a synchronous condenser on the 66 kV system. It seems that an almost infinitessimal voltage change causes an extremely large change in all the other quantities. It is believed this was caused by the instant response and regulating ability of the synchronous condensers.

In the case of the tests on the 66 kV system the voltage variation which could be realized was only 0.142 to 0.195%. This very small change caused an almost unbelievable change in the other three quantities. The current varied between a low of -8.85 to a high of 9.80%. The real power changed from a low of -6.74% to a high of -6.95%. The greatest response by far was that of the reactive power, changing from a low of 17.5% to a high of -19.7%. These results were not at all predictable.

In the case of exponents, table 1 shows extremely large numbers. The current exponents ranged from 40.60 to 63.65 while the real power ranged from 30.51 to a high of 45.96. The reactive power was again a great deal more sensitive to voltage change being between 73.73 and 116.71. These results were at first considered meaningless until several references were found, particularly one discussed in the general discussion[34].

The 33 kV supply at the Brandon station provided plausible results particularly the current and real power results. In the first set of tests on the 33 kV the voltage variation was approximately 0.75%. The change in current was on the average 0.687%. On the other hand the real power varied approximately 0.85% and the reactive power varied on the average 3.01%.

The comparison of exponents showed that the current was a function of the voltage raised to the approximate 0.9 power. The real power and reactive power were functions of the voltage to the 1.13 and 3.92 powers on the average.

In the second stage of the tests on the 33 kV supply a voltage change of about 1.5% was realized. This gave an approximate 1.5% change in the current, a 1.91% change in real power and a 7.23% in reactive power.

The exponents in table 1 show that with the 1.5% voltage variation the current is a function of the voltage to the 1.0 power. The real power and reactive power are functions to the 1.25 and 4.59 powers.

Raven Lake Station

In setting up the equipment at the Raven Lake Station some initial difficulties were experienced. It had been hoped to record the total load at the station before and after dropping one of the two transformer banks. This proved impossible because each of the two banks were being metered independently with a different current transformer ratio. Since the current transformers are situated in the bushings of the transformers it was not simple to do the necessary tap changes in the time allotted. It was therefore decided to take readings on the two 33 kV circuits emmanating from Raven Lake Station.

Another difficulty experienced at this station was the measurement of relatively small loads. The load at the station is not large, however, when each feeder was measured separately the load recorded was basically half as large. Because this load was small the amplifiers had to be used near their saturation limit, possibly not reducing the accuracy, but in any event magnifying unsuppressed harmonics in the transducer circuits. The inherent load variations and changes were much more troublesome than at other stations. By watching the lights of the recorder it could be seen that the normal load variations caused by random circumstances were of the same magnitude as the load changes due to voltage variation.

Because of the different ratings of the two banks (7.5 MVA and 15 MVA) two different voltage changes were possible on each of the two lines.

In the first series of tests on Line 86 a voltage change in the order of 0.322% caused a real power average change of 0.560%. As before, the reactive power was more sensitive with a change in the 3% range. The current appropriately was in the 0.45% area.

In the second stage of tests on Line 86 a change in voltage of 1.24% was attained. This voltage change caused a real power change of over 2% and an average reactive power change of 9.56%. The change in current was 1.37% on the average.

In looking at this same data from the point of view of the dependent quantities being functions of the voltage to some power, the results are illustrated in table 1.

In the case of the 0.322% voltage change the real power seems to be a function of the voltage raised to the 1.73 power. This power exponent remains about the same at 1.76 when the voltage is varied by 1.24% in the second part of the test on Line 86. The reactive power on the other hand seems to have a downward trend with larger voltage variation. Because the real power is a large component of the complex power the current follows the real power more closely than the reactive.

The same sort of voltage variations were performed on the load supplied by Line 88. The results are listed in table 1. In the first stage of the tests the voltage was varied by about 0.225%. In the second part of the tests the voltage was varied by slightly over 1%. As can be seen by the tabulations a small decrease in the response was found as the change in voltage increased. It is likely that if the voltage was varied by as much as 5% that a more predictable result would have been found.

Neepawa Station

The last station chosen to carry out tests at was the Neepawa Station. Similar results were found at this station. Again small voltage variations seemed to cause much more than predictable changes in the current, and reactive power. Real power appeared to be in line with what was expected. Because two matching transformers supply the Neepawa load only one magnitude of voltage change was possible.

In table 1 it can be seen that a voltage variation of 0.79% on the average causes an average change in power of 0.839%. This is also reflected by the tabulation of table 1 which shows the real power a function of the voltage raised to the approximate first power. This means the real power is proportional to the voltage or constant current.

The reactive power varies very drastically. Because of the size of the reactive power the current also varies very drastically with the voltage. It can be seen that the approximate 0.8% change in voltage causes an average 12% change in the reactive power and an average 12.3% change in current.

Table 1 also shows that the reactive power varies as the fourteenth power on the average and the current as the fifteenth power.

For ease in comparing the results from the different stations at which tests were taken table 2 is included. This table compares the average change in current, real and reactive power both in percentage and in exponential form.

TABLE 1

Variation of Current, Power, & Reactive Power with Voltage

Kirkfield Station (24 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-7.49%	2.56	-3.31%	1.15	-2.10%	0.74	-2.86%
2 (a)	-9.25	2.79	-3.64	1.13	-2.48	0.77	-3.22
(b)	7.80	2.62	3.33	1.15	2.48	0.86	2.90
3 (a)	-7.46	2.59	-3.18	1.13	-2.23	0.79	-2.82
(b)	7.65	2.56	3.48	1.19	2.52	0.86	2.92
4 (a)	-7.62	2.51	-3.12	1.05	-2.42	0.82	-2.97
(b)	8.25	2.84	3.04	1.07	2.16	0.77	2.83
avg.	7.93%	2.64	3.30%	1.12	2.34%	0.80	2.93%

TABLE 1 (continued)

St. Vital Station (66 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-5.12%	5.51	-2.47%	2.69	-2.01%	2.20	-0.910%
(b)	4.80	4.45	2.07	1.94	2.03	1.91	1.060
2 (a)	-5.26	5.92	-2.08	2.38	-2.26	2.58	-0.870
(b)	7.47	7.46	2.28	2.34	2.22	2.27	0.970
3 (a)	-5.09	5.14	-2.46	2.52	-2.41	2.47	-0.970
(b)	3.29	3.42	2.75	2.87	1.63	1.71	0.950
avg.	5.17%	5.31	2.35%	2.46	2.09%	2.19	0.955%

TABLE 1 (continued)

Parkdale Station (33 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-1.98%	6.77	-1.38%	4.73	-1.07%	3.68	-0.290%
(b)	1.67	6.91	1.07	4.44	0.910	3.78	0.240
2 (a)	-1.44	6.51	-0.940	4.26	-0.710	3.22	-0.220
(b)	0.720	6.53	0.770	6.98	0.370	3.36	0.110
3 (a)	-1.63	4.91	-1.12	3.38	-0.930	2.81	-0.330
(b)	1.10	4.21	0.890	3.41	0.490	1.88	0.260
4 (a)	-1.67	5.92	-1.20	4.27	-1.09	3.88	-0.280
(b)	2.06	7.29	0.620	2.21	0.630	2.25	0.280
avg.	1.53%	6.13	1.00%	4.21	0.775%	3.11	0.251%

TABLE 1 (continued)

Rosenfeld Station (66 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-6.79%	15.14	-4.59%	10.34	-0.787%	1.81	-0.435%
(b)	5.35	16.62	3.33	10.45	0.715	2.27	0.314
2 (a)	-5.82	17.71	-2.39	7.39	-0.692	2.16	-0.320
(b)	5.11	20.28	1.26	5.10	0.597	2.42	0.246
3 (a)	-5.66	17.62	-2.49	7.87	-0.753	2.40	-0.313
(b)	5.78	23.94	2.42	10.19	0.676	2.87	0.235
avg.	5.75%	18.55	2.75%	8.56	0.703%	2.32	0.311%

TABLE 1 (continued)

Brandon Station (66 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-19.7%	92.31	-6.95%	34.49	-9.40%	46.12	-0.195%
(b)	17.5	73.73	6.90	30.51	9.29	40.60	0.195
2 (a)	-19.1	115.09	-6.90	43.93	-9.25	58.25	-0.152
(b)	18.7	116.71	6.88	45.30	9.80	63.65	0.147
3 (a)	-17.8	115.44	-6.74	45.96	-8.85	59.76	-0.142
(b)	19.6	97.89	6.75	35.72	8.80	46.13	0.183
avg.	18.7%	101.86	6.85%	39.32	9.23%	52.42	0.169%

TABLE 1 (continued)

Brandon Station (33 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-3.00%	3.83	-0.906%	1.17	-0.700%	0.900	-0.775%
(b)	2.80	3.90	0.693	0.980	0.580	0.820	0.710
2 (a)	-3.06	3.67	-0.908	1.10	-0.736	0.890	-0.825
(b)	3.03	3.92	0.897	1.17	0.715	0.930	0.765
3 (a)	-2.98	4.08	-0.821	1.13	-0.669	0.930	-0.723
(b)	3.20	4.13	0.935	1.22	0.723	0.950	0.765
avg.	3.01	3.92	0.860	1.13	0.687	0.903	0.761
4 (a)	-6.69	3.78	-1.97	1.14	-1.36	0.790	-1.73
(b)	7.90	4.94	1.74	1.12	1.54	0.990	1.55
5 (a)	-7.43	4.81	-2.12	1.41	-1.59	1.06	-1.50
(b)	7.56	4.89	1.94	1.29	1.48	0.990	1.50
6 (a)	-6.94	4.57	-1.86	1.25	-1.42	0.960	-1.48
(b)	6.85	4.57	1.84	1.26	1.64	1.12	1.46
avg.	7.23%	4.59	1.91%	1.25	1.51%	0.985	1.54%

TABLE 1 (continued)

Raven Lake Station (33 kV) - Line 86

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-2.92%	8.66	-0.610%	1.83	-0.487%	1.46	-0.333%
(b)	3.30	10.46	0.510	1.64	0.421	1.35	0.311
avg.	3.11	9.56	0.560	1.73	0.454	1.41	0.322
2 (a)	-8.15	6.41	-2.12	1.72	-1.33	1.08	-1.23
(b)	8.90	7.09	2.19	1.80	1.22	1.01	1.21
3 (a)	-9.88	7.83	-2.27	1.87	-1.72	1.42	-1.21
(b)	11.30	8.23	2.16	1.64	1.22	0.930	1.31
avg.	9.56%	7.39	2.19%	1.76	1.37%	1.11	1.24%

TABLE 1 (continued)

Raven Lake Station (33 kV) - Line 88

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-0.965%	4.62	-0.315%	1.51	-0.204%	0.980	-0.208%
(b)	1.55	8.23	0.342	1.83	0.286	1.53	0.187
2 (a)	-2.30	7.03	-0.579	1.78	-0.745	2.29	-0.324
(b)	1.36	10.73	0.452	3.58	0.332	2.63	0.126
3 (a)	-2.62	9.38	-0.726	2.62	-0.586	2.12	-0.276
(b)	1.64	7.14	0.389	1.70	0.224	0.980	0.228
avg.	1.74	7.86	0.467	2.17	0.396	1.76	0.225%
4 (a)	-6.55	5.70	-2.12	1.88	-1.33	1.19	-1.12
(b)	6.78	6.22	1.97	1.85	1.27	1.20	1.06
5 (a)	-6.85	5.79	-2.12	1.83	-1.15	1.00	-1.15
(b)	7.32	6.46	2.23	2.02	1.52	1.38	1.10
avg.	6.88%	6.04	2.11%	1.90	1.32%	1.19	1.11%

TABLE 1 (continued)

Neepawa Station (66 kV)

Test No.	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
1 (a)	-10.45%	14.45	-0.728%	1.05	-11.05%	15.24	-0.690%
(b)	15.10	15.52	1.06	1.16	13.00	13.49	0.910
2 (a)	-7.88	12.47	-0.652	1.07	-11.15	17.38	-0.610
(b)	15.90	14.54	1.30	1.27	12.43	11.54	1.02
3 (a)	-10.20	13.73	-0.682	0.960	-13.65	18.09	-0.710
(b)	12.70	15.04	0.610	0.770	12.60	14.93	0.798
avg.	12.04%	14.29	0.839%	1.05	12.31%	15.11	0.790%

TABLE 2

Comparison of Average Station Test Data

Station	Reactive Power		Power		Current		Voltage
	in %	exponent	in %	exponent	in %	exponent	in %
Kirkfield (24 kV)	7.93%	2.64	3.30%	1.12	2.34%	0.80	2.93%
St. Vital (66 kV)	5.17	5.31	2.35	2.46	2.09	2.19	0.955
Parkdale (33 kV)	1.53	6.13	1.00	4.21	0.775	3.11	0.251
Rosenfeld (66 kV)	5.75	18.55	2.75	8.56	0.703	2.32	0.311
Brandon (66 kV)	18.7	101.86	6.85	39.32	9.23	52.42	0.169
Brandon (33 kV)	3.01	3.92	0.860	1.13	0.687	0.903	0.761
	7.23	4.59	1.91	1.25	1.51	0.985	1.54
Raven Lake (33 kV)	3.11	9.56	0.560	1.73	0.454	1.41	0.322
Line 86	9.56	7.39	2.19	1.76	1.37	1.11	1.24
Raven Lake (33 kV)	1.74	7.86	0.467	2.17	0.396	1.76	0.225
Line 88	6.88	6.04	2.11	1.90	1.32	1.19	1.11
Neepawa (66 kV)	12.04%	14.29	0.839%	1.05	12.31%	15.11	0.790%

CHAPTER V

CONCLUSIONS

The tests from which data tabulated here was obtained and any conclusions derived from them are constrained by the fact that the voltage changes were small, all changes being less than 5%. With this in mind, the five main findings were:

1. The reactive power is much more sensitive to voltage change than real power.

In all tests carried out on the Manitoba System the reactive power responded more to voltage changes than the real power. There is also ample evidence in the literature to support this statement[31, 34]. Many utilities use a constant current representation for the real power and a constant impedance representation for the reactive power.

2. The real and reactive power are both more sensitive to voltage change than was expected or predicted by conventional load representation.

This is evident from the test data which shows the reactive power normally varying to a greater power of the voltage than two, and the real power varying to a greater power of the voltage than one.

3. The change in real and reactive power becomes less sensitive to voltage as the change in voltage increases. The changes in real and reactive power are functions of the

magnitude of the voltage change.

Even though large voltage variations were not carried out on the system tested a trend seemed to be established that indicated greater percentage changes in smaller variations in voltage and considerably less change in the 2 - 3% region. The curves of change in real and reactive power level out in the 2 - 3% area as shown in figures 5 and 6.

It is possible to install automatic recording equipment to measure quantities required during system disturbances. Circuits such as those used in "delta - omega" stabilizers for modern generators are suitable for measuring rapid changes in frequency. There has been some research carried out along these lines by Ontario Hydro[39]. Voltage recording equipment for measuring rapid voltage variations is readily available and can be operated automatically. The main difficulty in installing automatic recording equipment is that normally there are voltage and frequency excursions occurring simultaneously. A good example of such an occurance is a fault on a system. Generators near the fault electrically, will speed up causing the frequency to increase. The voltage near the fault will drop. In other parts of the system, because of the deficiency in generation, the frequency will fall as well as the voltage. It is difficult and likely impossible to assess which part of the change in load was caused by the voltage change and which by the frequency change.

4. For large voltage changes the real and reactive power functions approach the relationships:

$$P = k_P V \qquad (5 - 1)$$

$$Q = k_Q V^3 \qquad (5 - 2)$$

Representaing the real power as constant current and reactive power as constant impedance would give results that would normally show a system a little less stable than it would be under actual conditions. This is probably the type of representation that would please most system analysts since it is simple and an average for the whole system. Also many digital stability programs will not converge when a system is subjected to a severe disturbance unless the load is a function of voltage.

5. The time constant for loads is much shorter than previously assumed.

The curves showing both real and reactive power variation with voltage have time constants in the 300 msec range. It was found that almost all this delay was in the metering circuits. The time constant of the load is actually in the 1 - 2 cycle area. It would be a good approximation to say that for the transient time period which on the average may be about half a second after a disturbance the load has already reached its new steady state value.

It is evident from the tests carried out on the Manitoba Hydro system that the behaviour and composition of loads varies a great deal. This can readily be understood when it is recalled that loads are essentially distributed in a random fashion geographically, depending on the location of natural resources, transportation facilities, government action, climate, and a great deal of other reasons. Besides the actual location of loads the composition of them depends on a great deal of other variables. These variables are as diverse as the standard of living, acceptance of new techniques or products, availability of competing products and advertising. It can be seen that because of the many variables loads in some areas can be almost purely resistive while in other areas large motor content means large reactive requirements. Because of this load mix it is not possible to ever define loads precisely for all systems, even all loads on the same system. It is, however possible to define loads at major stations. In most stability studies these major stations have equivalent loads represented on their bus. It is quite common to reduce systems further, often to the point where the Manitoba system would be represented by only a handful of machines, interconnected impedances and loads.

To obtain accurate results voltage changes starting from say 1% up to 10% should have been made. This type of experiment is possible in a lab, however there is no means of varying the voltage by successively larger steps at major supply points.

When the tests were first organized it was decided to study load behaviour at major supply points. In transient stability studies the system is not normally represented beyond these major supply points. It would also be a very large project to carry out any comprehensive tests on the several hundred substations in Manitoba. Nonetheless, information obtained on individual substations could be obtained using sampling techniques. Most urban substations are equipped with on-load tap-changers and many of the new rural substations are now also so equipped. The regulating range is ±10% so that stepped voltage changes can be obtained by parallelling two transformers on dissimilar taps. This would be an excellent future research area.

APPENDIXES

APPENDIX A

Sensitivity Measurements

SENSITIVITY MEASUREMENTS

This information is included as backup to data and information on measurements.

Galvanometer Sensitivity   0.564 v/inch or 1.7 inches/volt

Voltage Sensitivity	40 mvDC/volt	115 volts = 4.5 vDC
Current "	900 mvDC/amp.	5 amps. = 4.5 vDC
Reactive Power "	4.4 mvDC/VAR	1000 VARs = 4.4 vDC
Real Power "	4.4 mvDC/watt	1000 watts = 4.4 vDC

Voltage Sensitivity of a 1 Volt Change:

Amplifier Gain	Potential Difference (in millivolts)	Deflection (in inches)
x 1	40	0.0708
x 2	80	0.1436
x 5	200	0.354
x 10	400	0.708

Current Sensitivity of a 1 Ampere Change:

Amplifier Gain	Potential Difference (in millivolts)	Deflection (in inches)
x 1	900	1.60
x 2	1800	3.20
x 5	4500	8.00
x 10	9000	16.00

Reactive Power Sensitivity of a 1 VAR Change:

Amplifier Gain	Potential Difference (in millivolts)	Deflection (in inches)
x 1	4.4	0.007
x 2	8.8	0.014
x 5	22.0	0.035
x 10	44.0	0.070
x 20	88.0	0.140

Real Power Sensitivity of a 1 Watt Change:

Amplifier Gain	Potential Difference (in millivolts)	Deflection (in inches)
x 1	4.4	0.007
x 2	8.8	0.014
x 5	22.0	0.035
x 10	44.0	0.070
x 20	88.0	0.140

APPENDIX B

TABLE 3

Biased Loads, Gains, and Multipliers

Listed in Table 3, for each test location are the biased loads — the actual load in VARs, Watts or amperes or the actual voltage applied. The bias voltage for each of the quantities was increased from zero until it exactly equaled the voltage output from the transducers. The biased quantities therefore represent the starting conditions of the varying quantities. The amplifier gain is tabulated to document the degree of amplification required for each quantity. The multiplier is simply the product of current and potential transformers in use at each station.

TABLE 3

Biased Loads, Gains, and Multipliers

Kirkfield Station (24 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
660.0 VARs	5	32,000
1280.0 Watts	5	32,000
124.0 Volts	5	200
6.7 Amperes	1	160

TABLE 3 (continued)

St. Vital Station (66 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
160.7 VARs	5	33,000
960.0 Watts	5	33,000
123.5 Volts	5	550
4.4 Amperes	2	60

Parkdale Station (33 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
188.0 VARs	10	16,500
770.0 Watts	10	16,500
126.4 Volts	10	275
3.3 Amperes	10	60

Rosenfeld Station (66 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
91.0 VARs	10	16,500
860.0 Watts	10	16,500
126.2 Volts	10	550
4.1 Amperes	10	30

TABLE 3 (continued)

Brandon Station (66 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
68.0 VARs	5	36,000
704.0 Watts	5	36,000
116.0 Volts	10	600
3.5 Amperes	5	60

Brandon Station (33 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
445.0 VARs	10	24,800
1060.0 Watts	10	33,000
126.0 Volts	10	275
2.2 Amperes	10	120

Raven Lake Station (33 kV) - Line 88

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
136.0 VARs	10	8,280
544.0 Watts	10	8,280
128.0 Volts	10	275
4.9 Amperes	10	30

TABLE 3 (continued)

Raven Lake Station (33 kV) - Line 86

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
91.0 VARs	10	8,280
742.0 Watts	10	8,280
129.0 Volts	10	275
5.6 Amperes	10	20

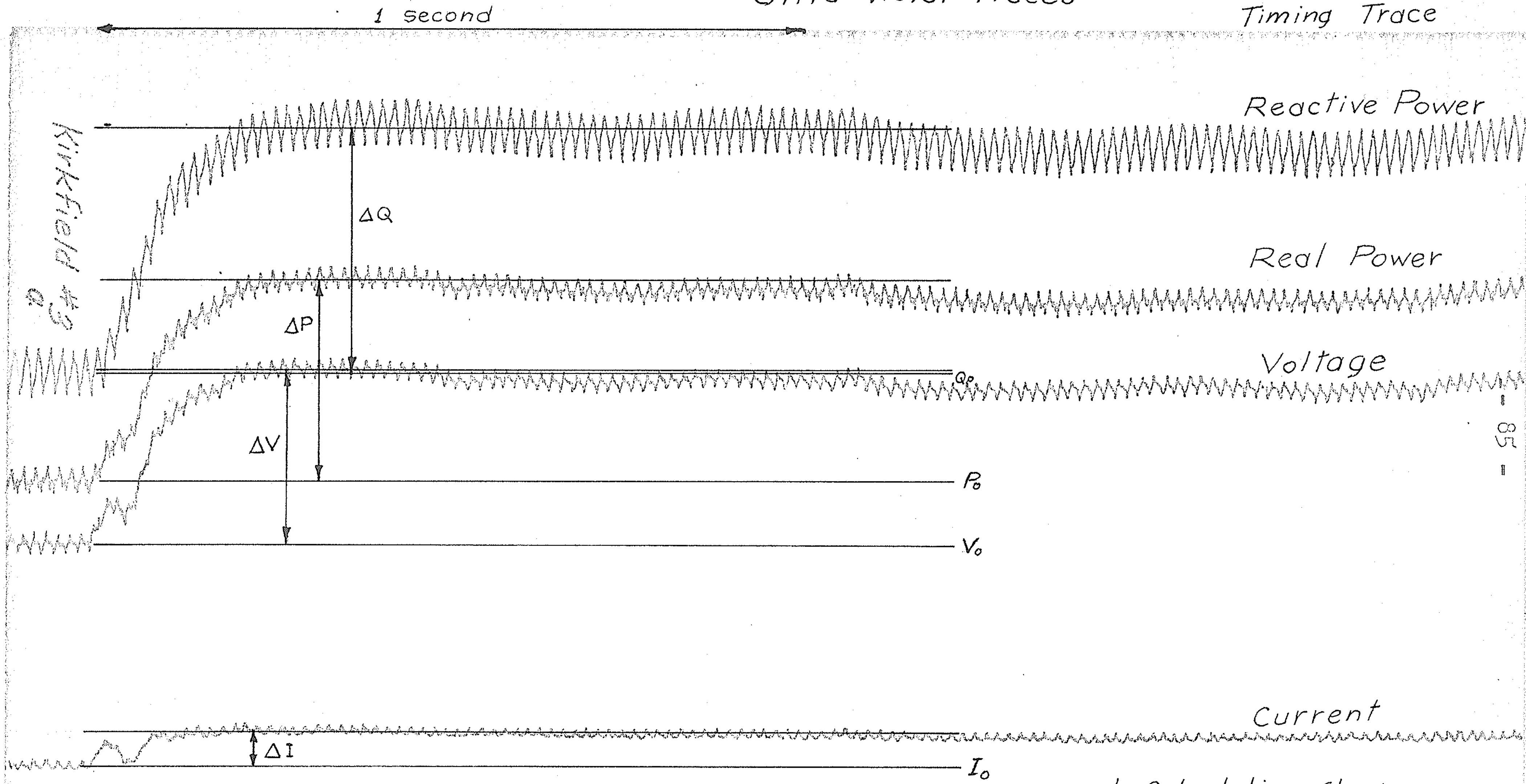
Neepawa Station (66 kV)

Biased Readings (Secondary Quantities)	Amplifier Gain	Multiplier
45.5 VARs	10	22,000
944.0 Watts	10	22,000
125.2 Volts	10	550
4.4 Amperes	10	40

APPENDIX C

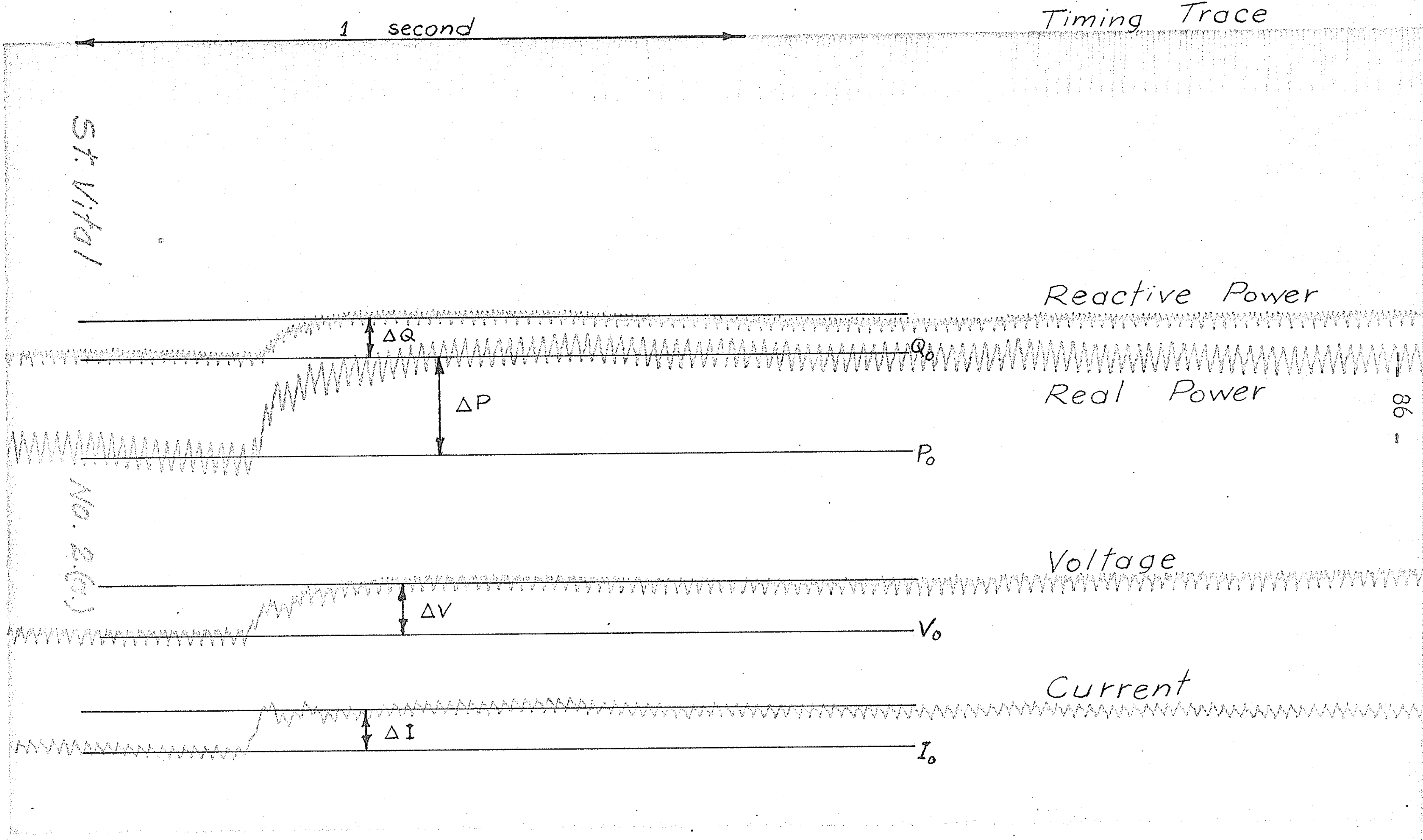
Examples of Traces

Ultra-Violet Traces



Sample Calculation shown
on page 45

Ultra-Violet Traces



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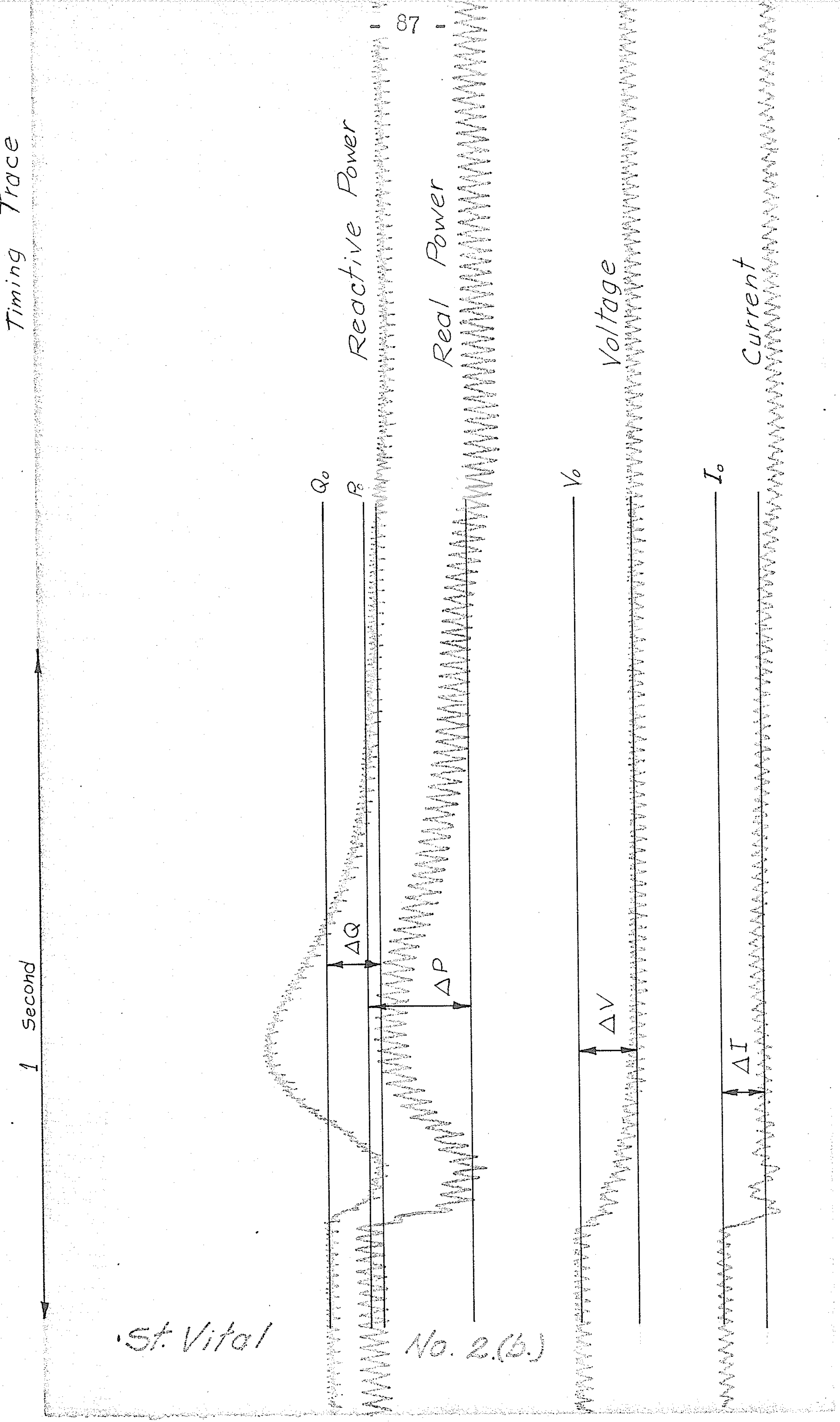
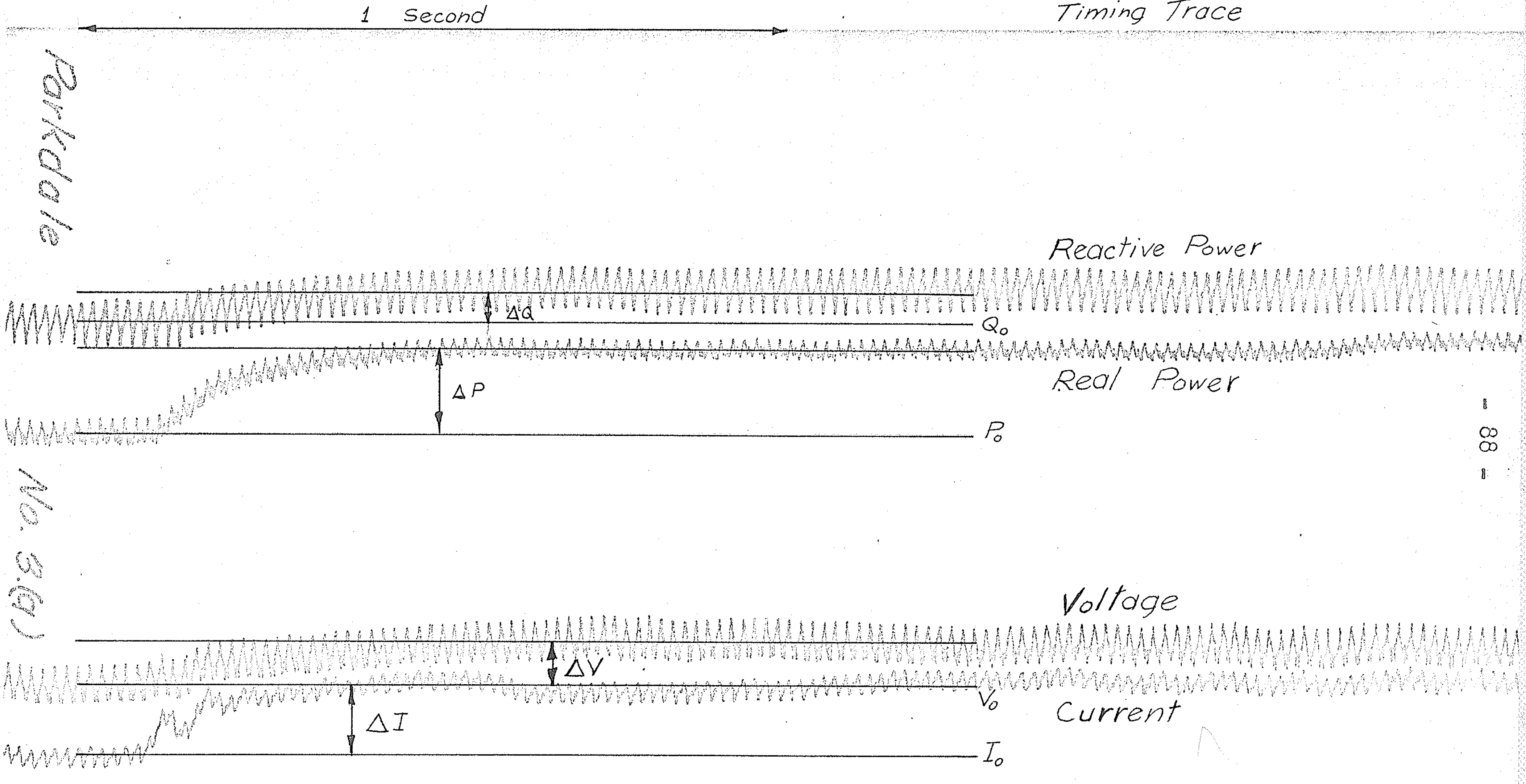


St. Vital No. 2.(b.)

Ultra - Violet Traces



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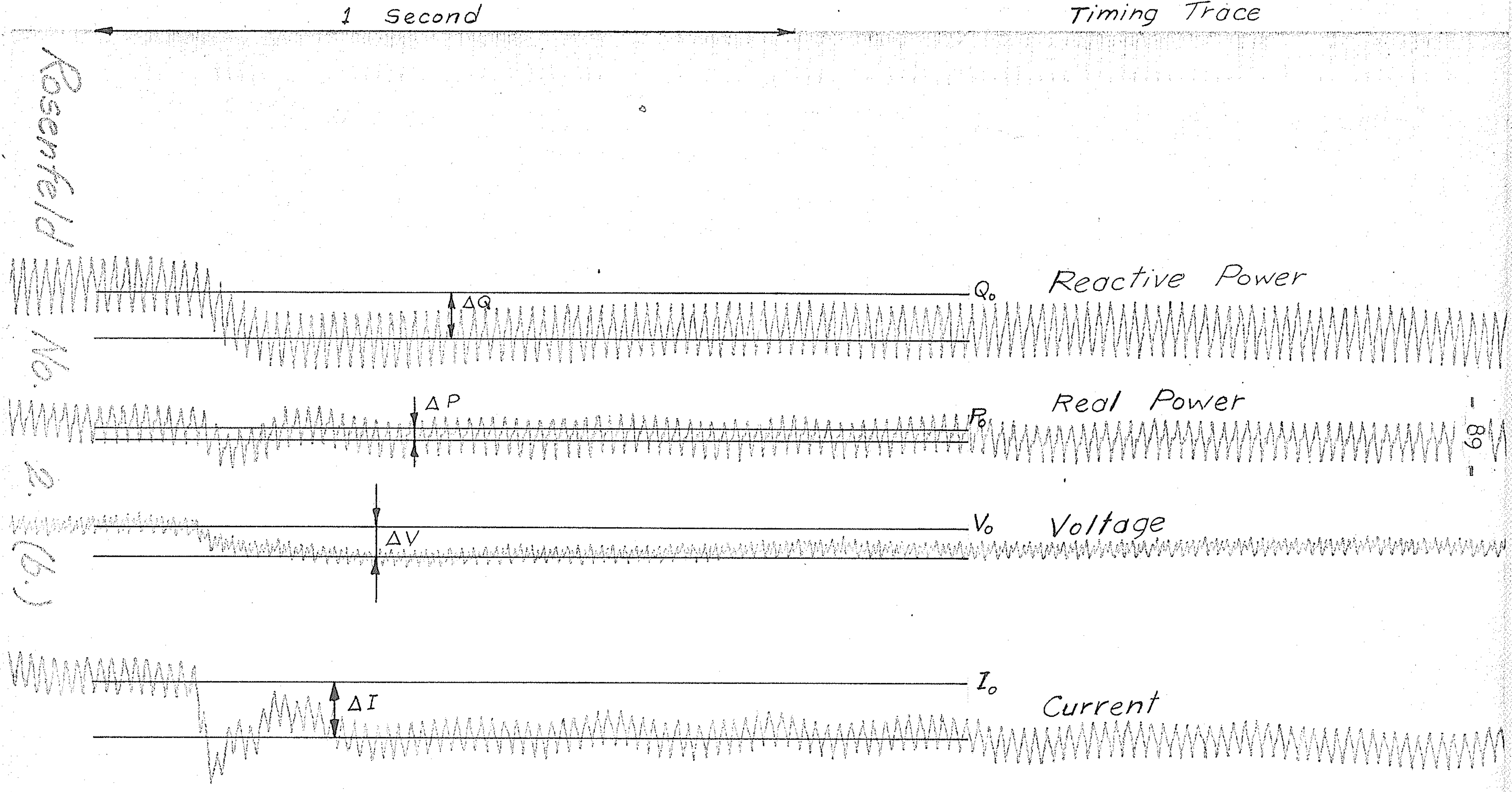
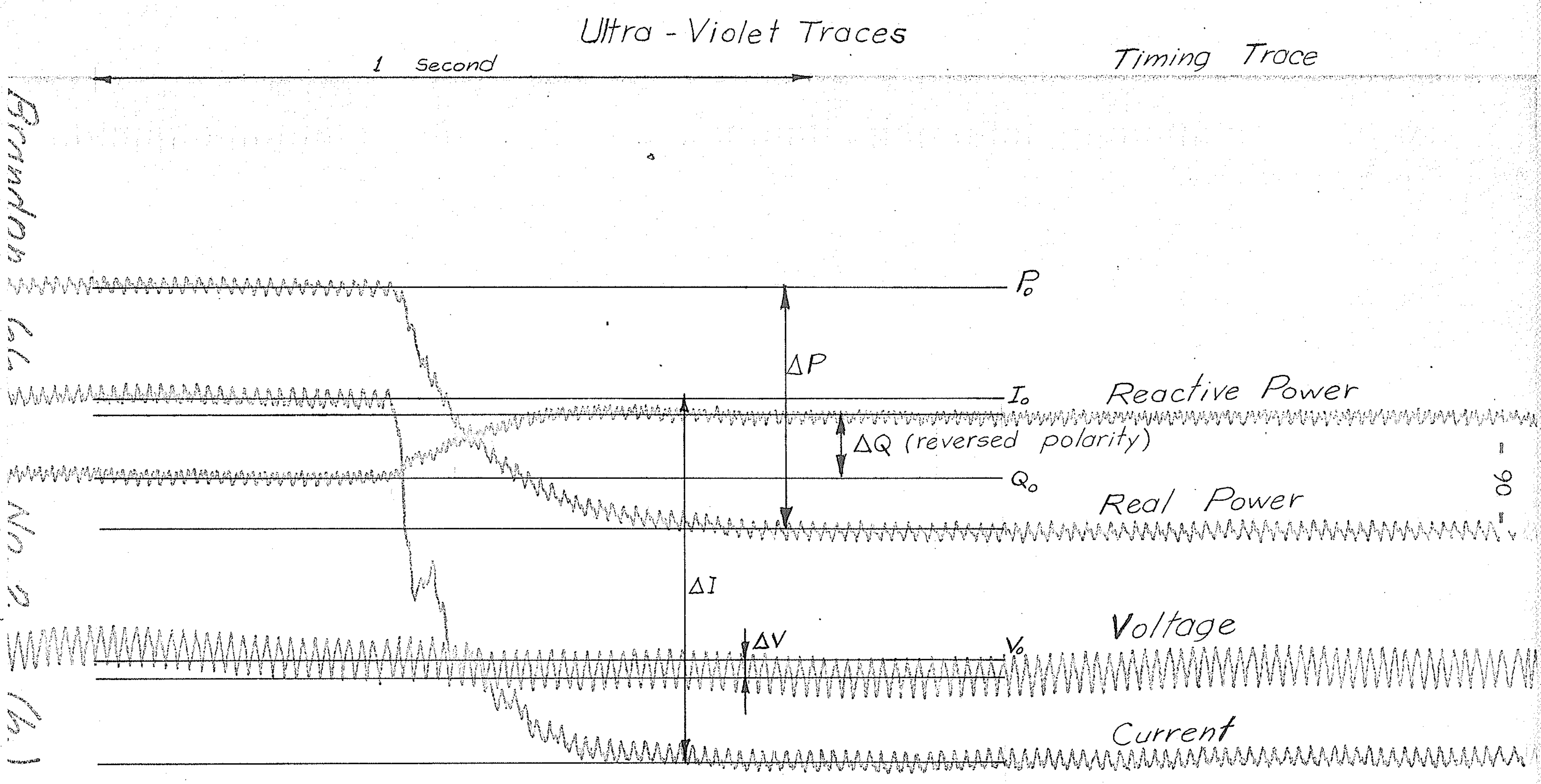
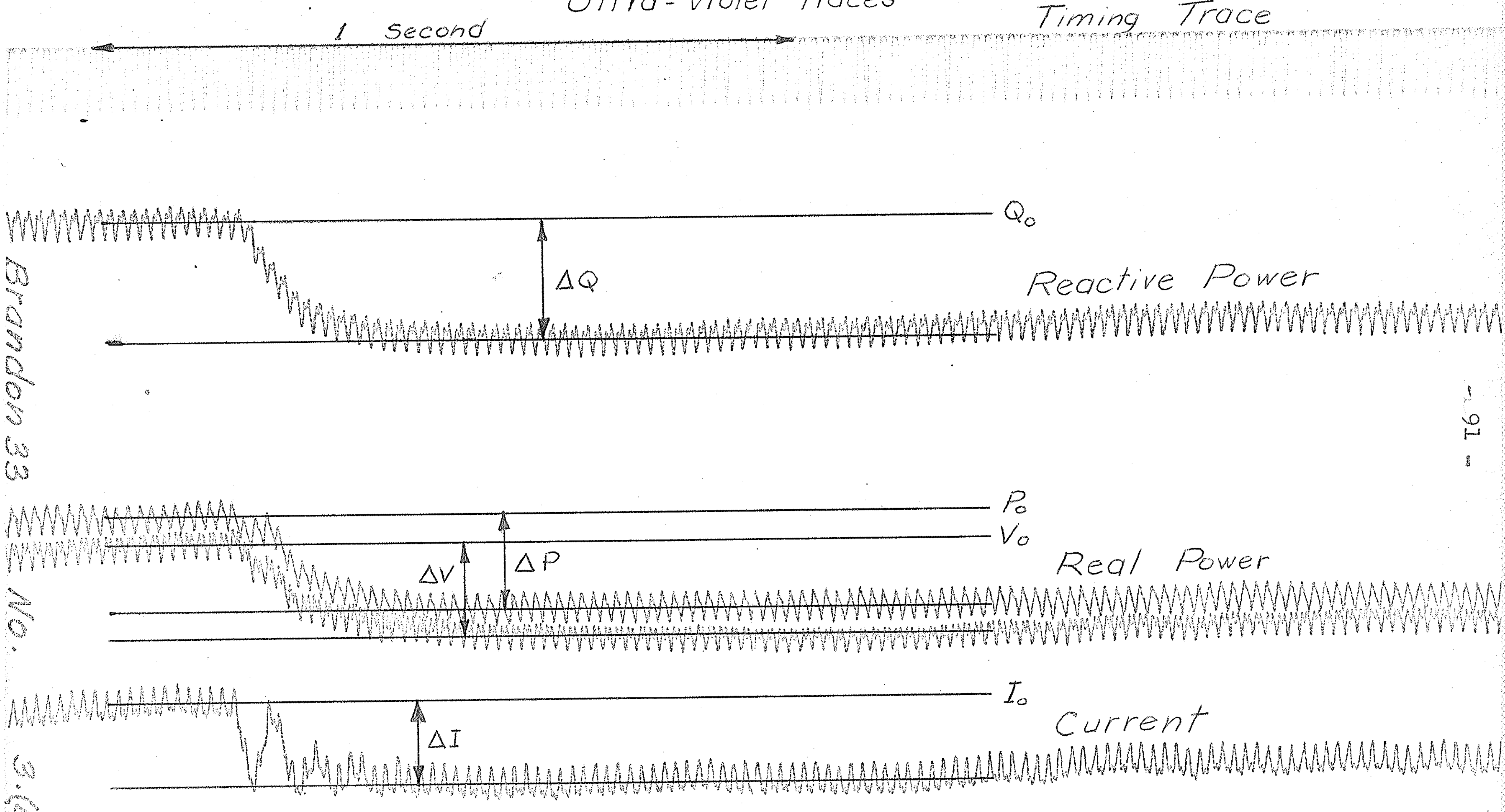


Rosenfeld No. 2. (b.)

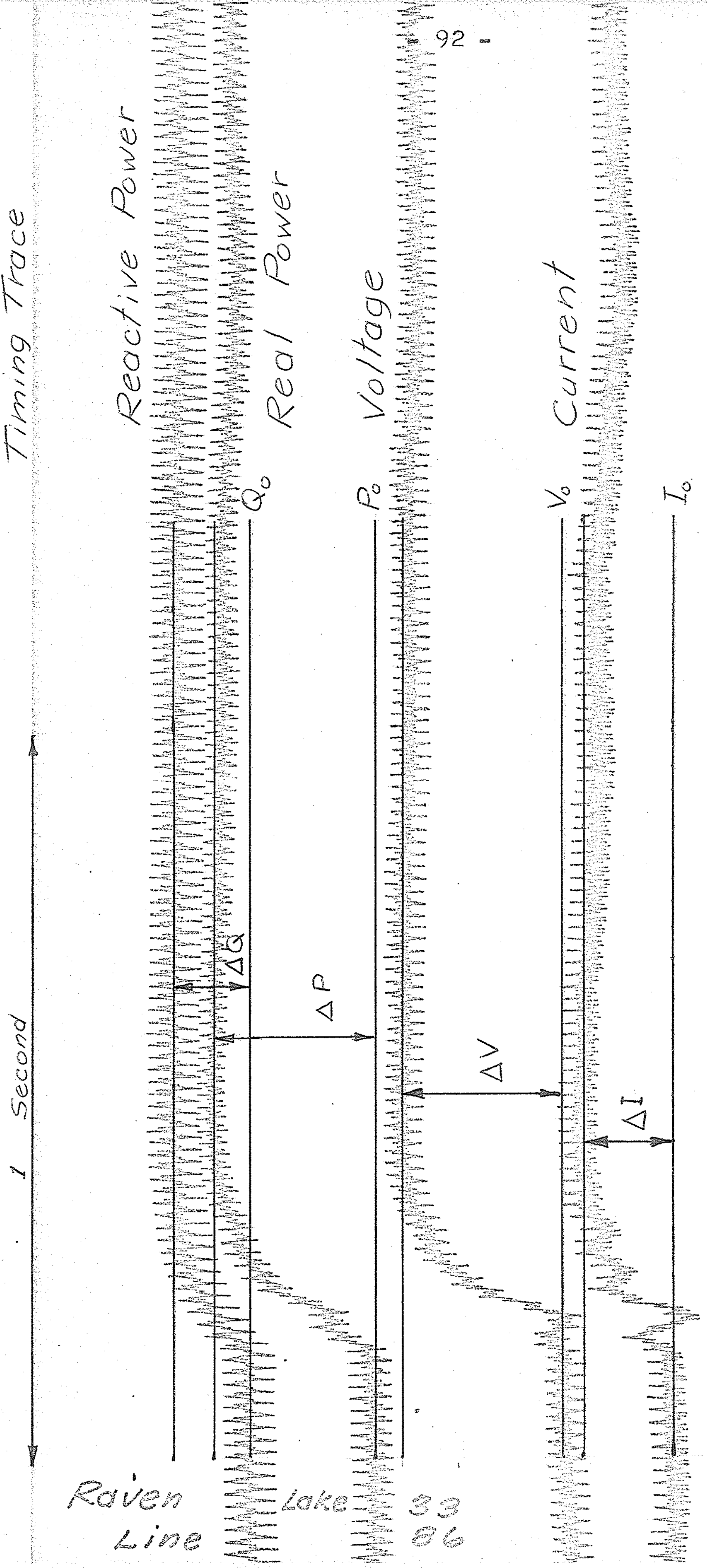


Ultra - Violet Traces

Ultra-Violet Traces

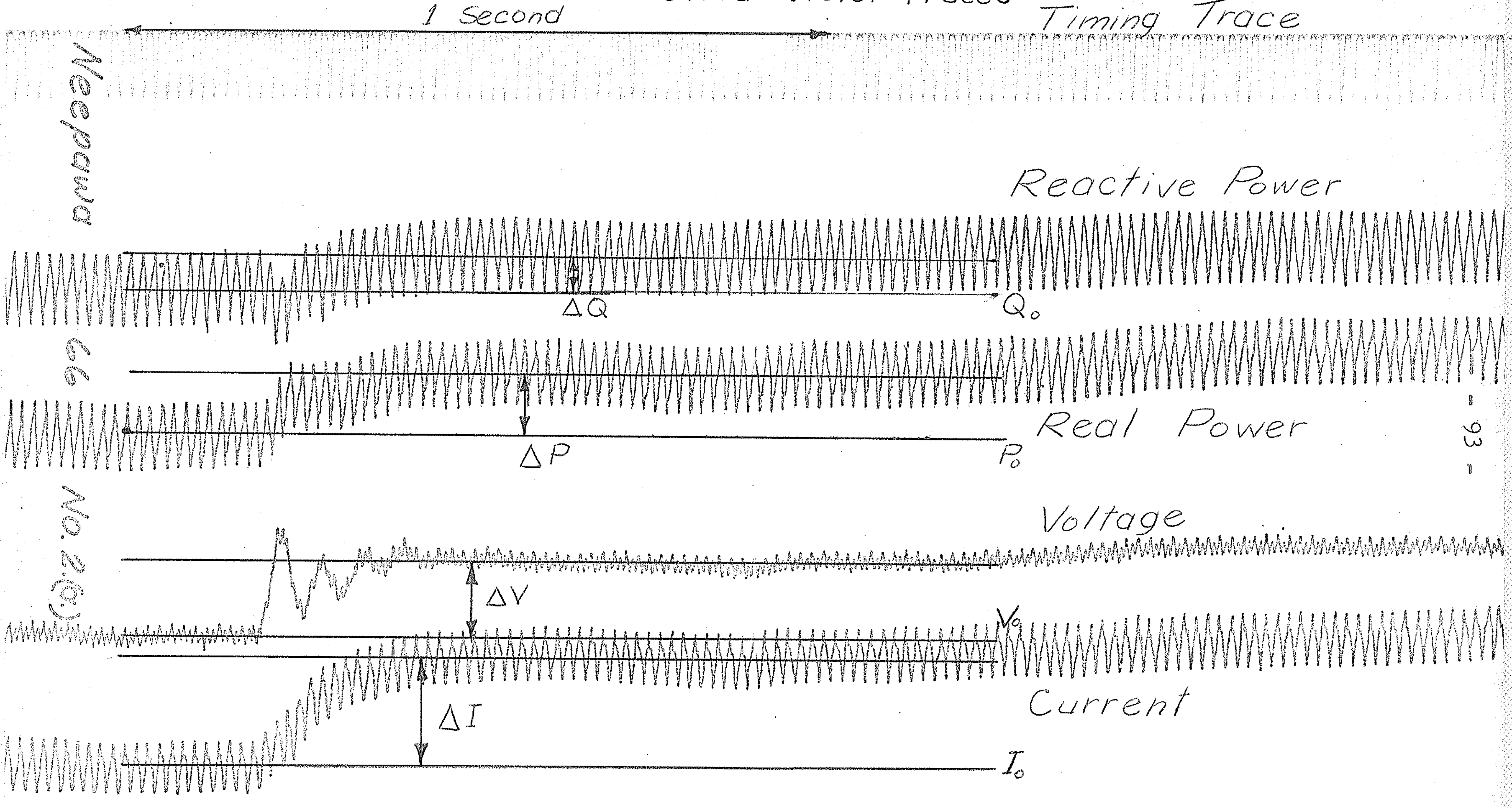


Brandon 33 No. 3.(b.)

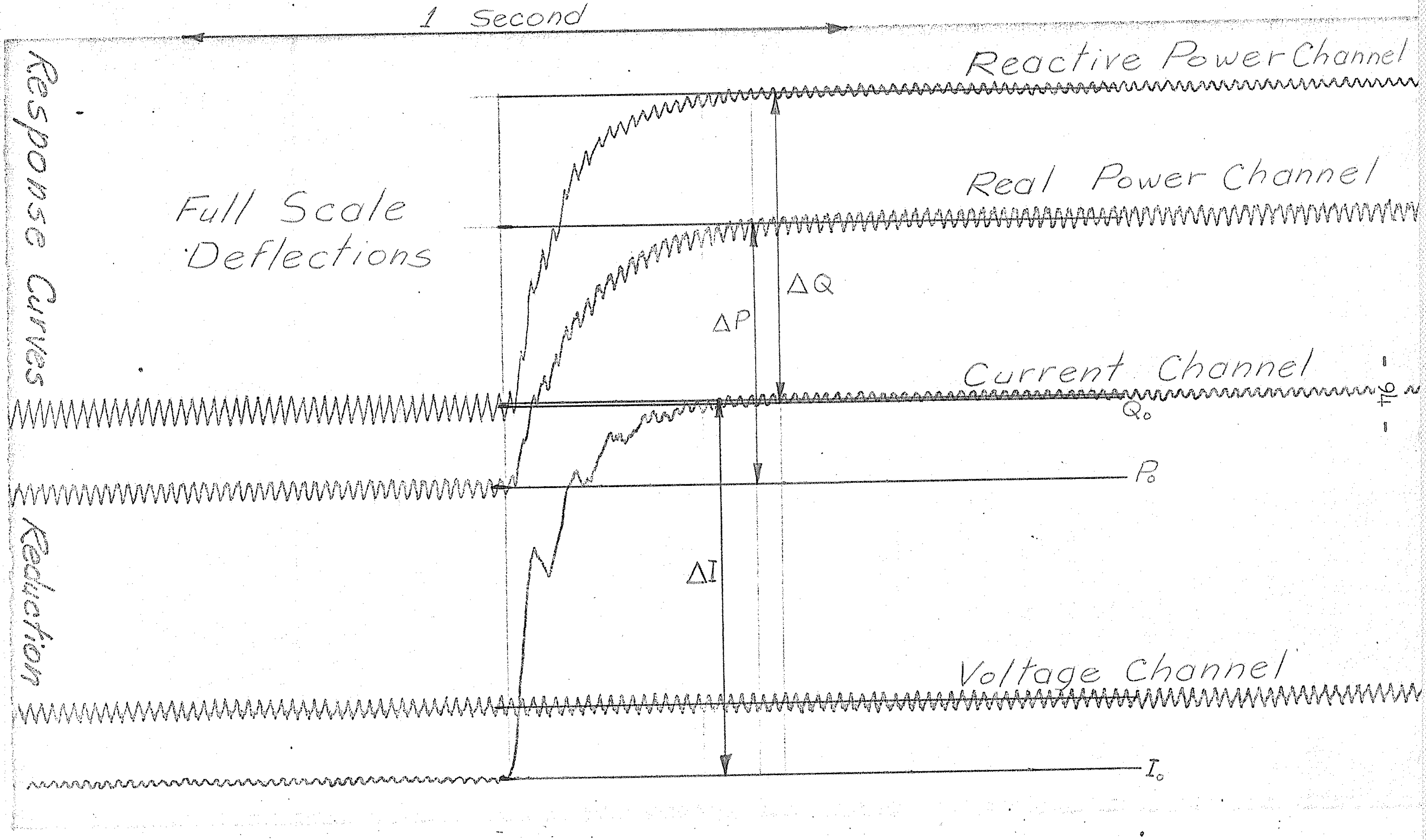

Ultra-Violet Traces

No. 2 (a)

Ultra-Violet Traces

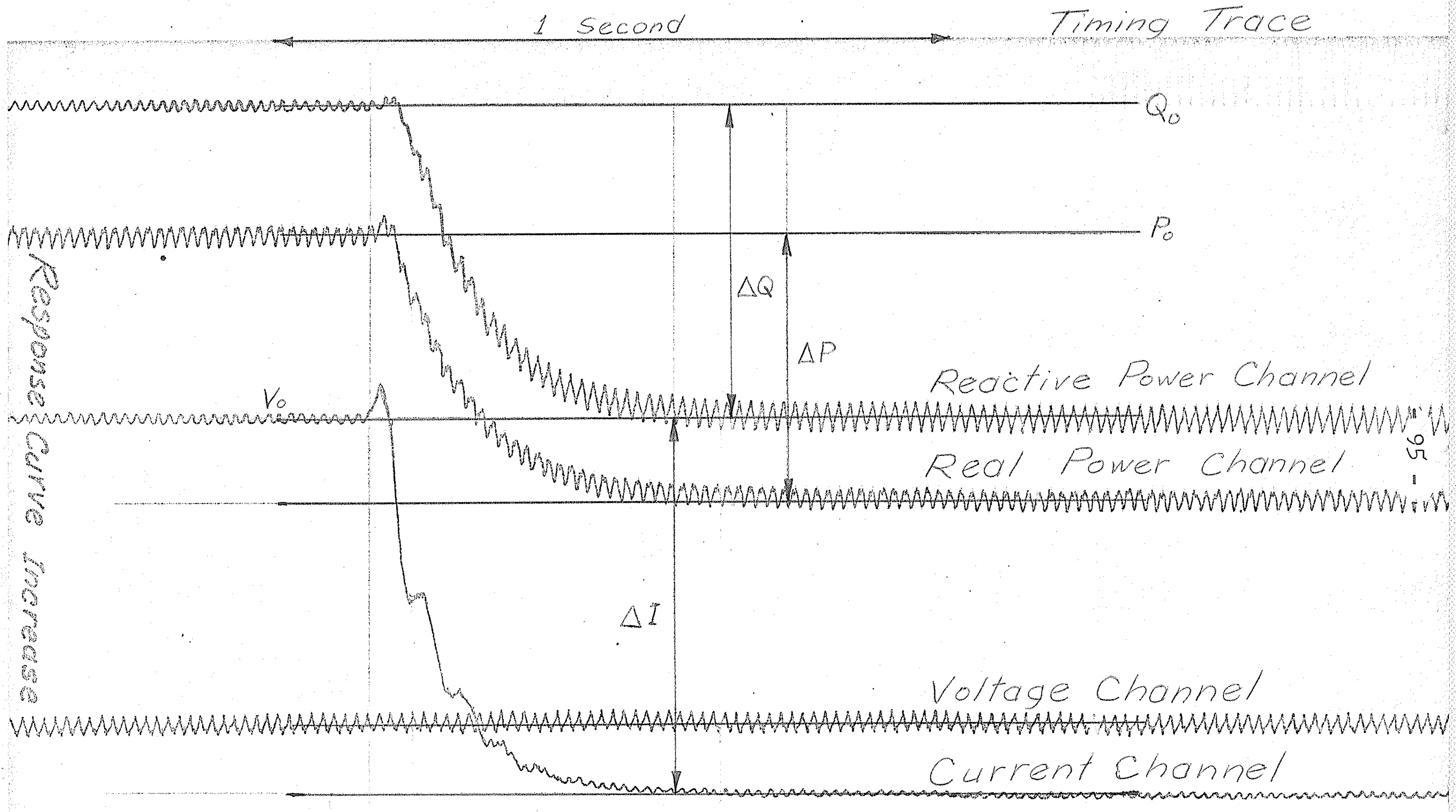


Ultra-Violet Traces - Shop Tests.



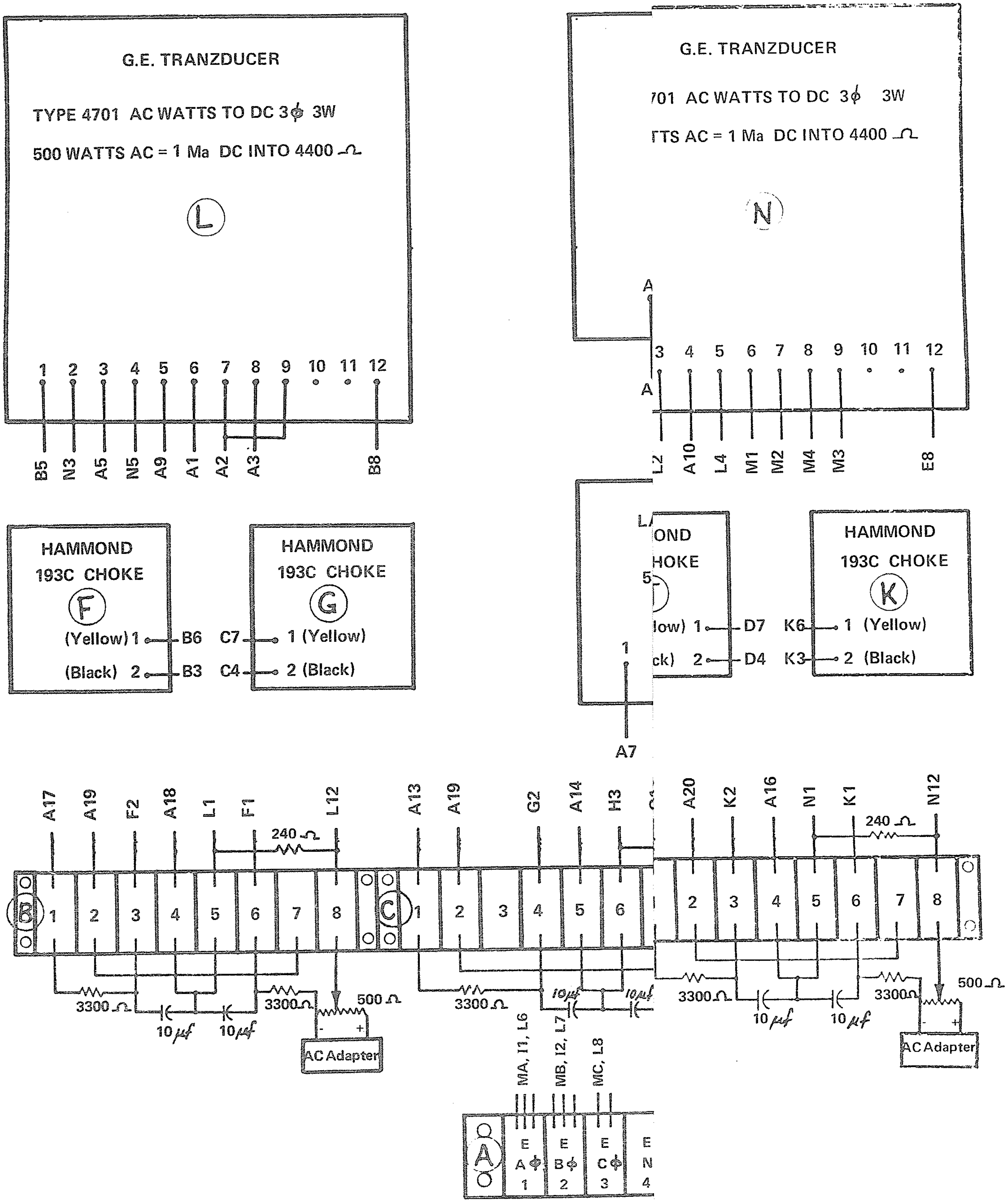
Ultra-Violet Traces - Shop Tests

Full Scale Deflections



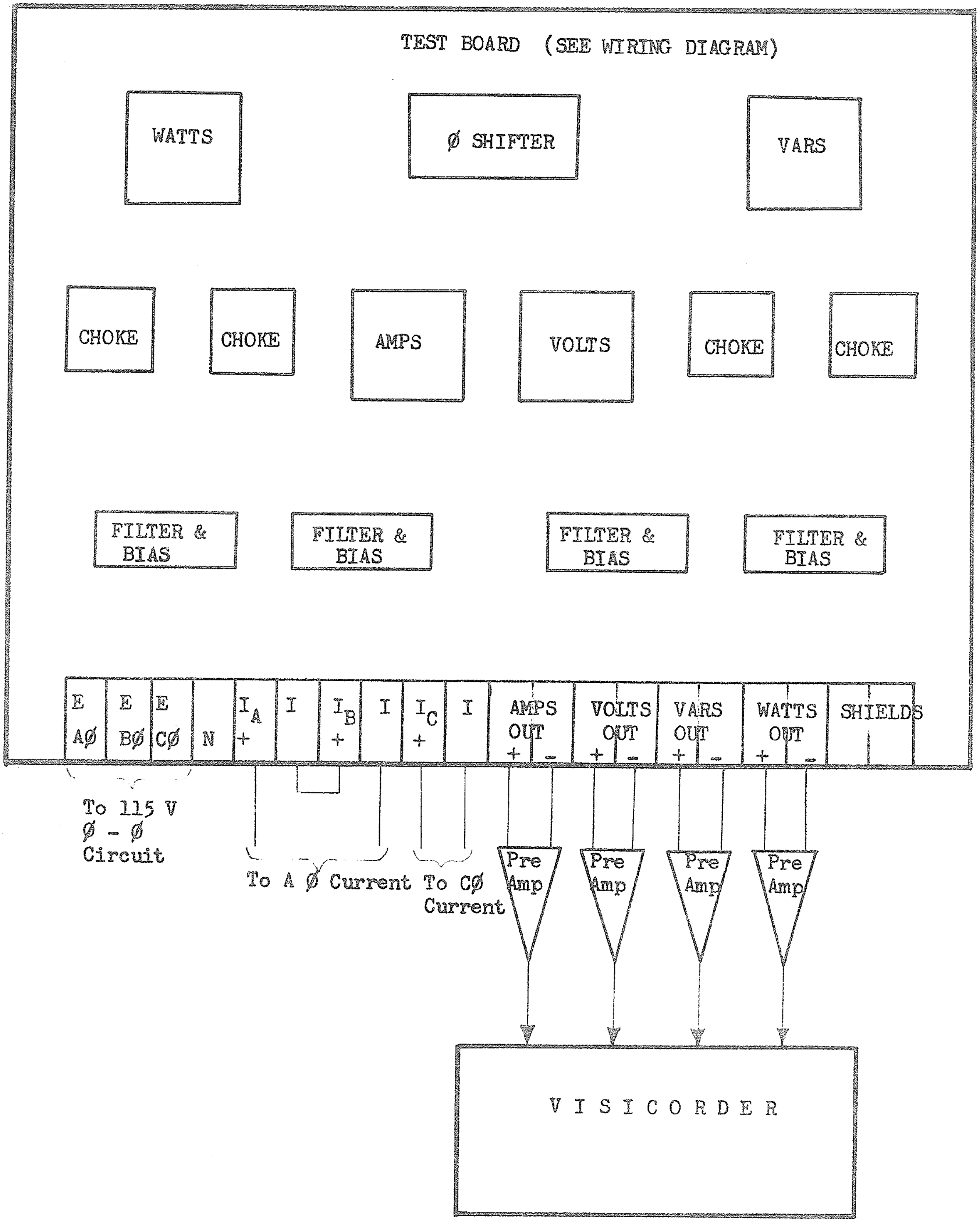
APPENDIX D

Figures



NB. AC ADAPTERS PLUG I

VOLTAGE VARIATION TESTS
DIAGRAM Figure 8



TRANSIENT LOAD - VOLTAGE VARIATION TESTS
TEST BOARD ARRANGEMENTS Figure 9

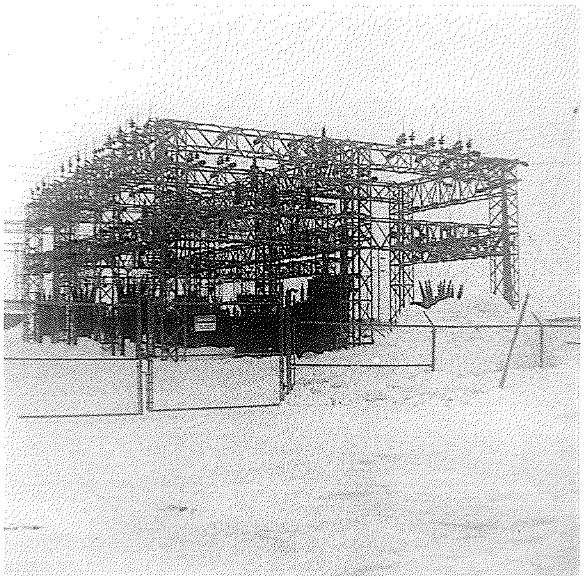


Fig. 10

Kirkfield Station

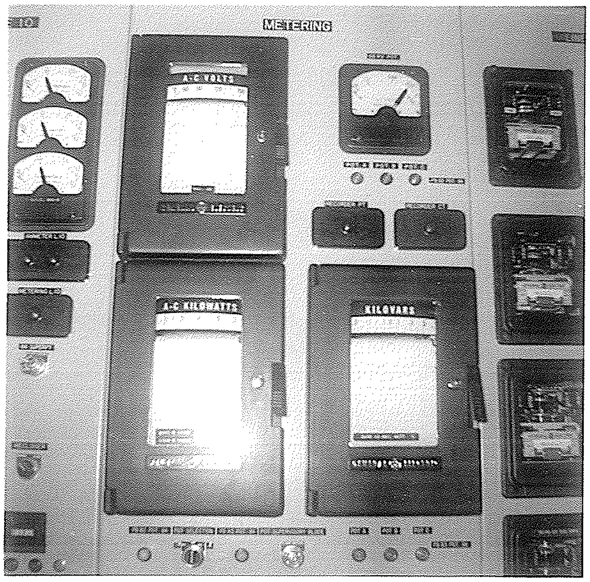


Fig. 11

Metering at Kirkfield

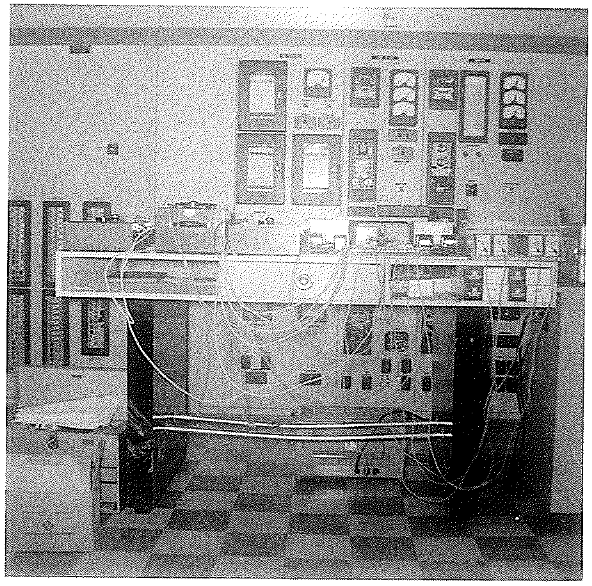


Fig. 12

Recording Setup at

Kirkfield Station

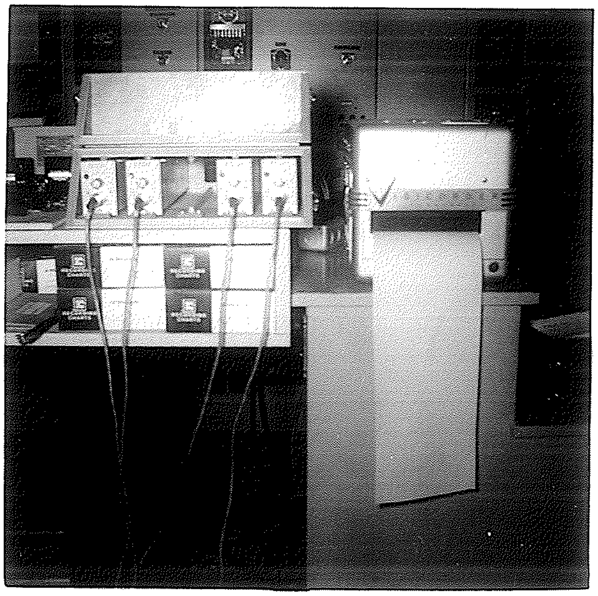


Fig. 13

Amplifiers and Visicorder

at Kirkfield

Fig. 14

Power Supplies and Transducers at Kirkfield

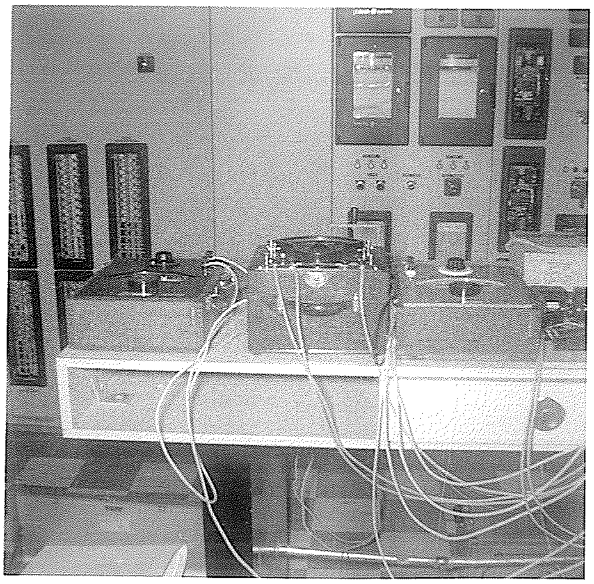


Fig. 15

Measuring Instruments at Kirkfield

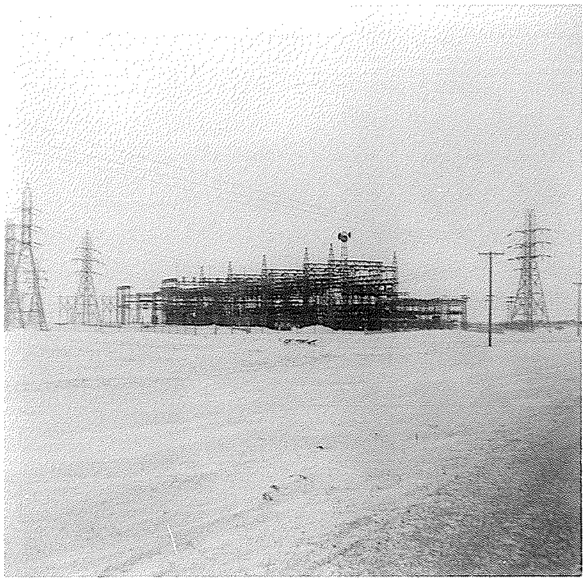


Fig. 16

Parkdale Station

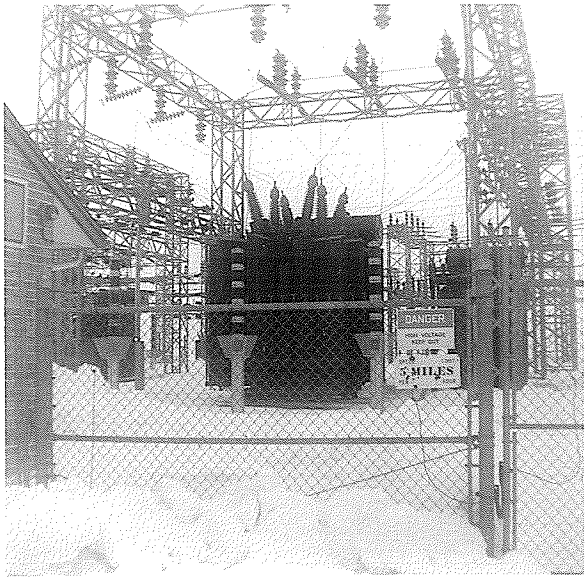


Fig. 17

Transformer at Parkdale

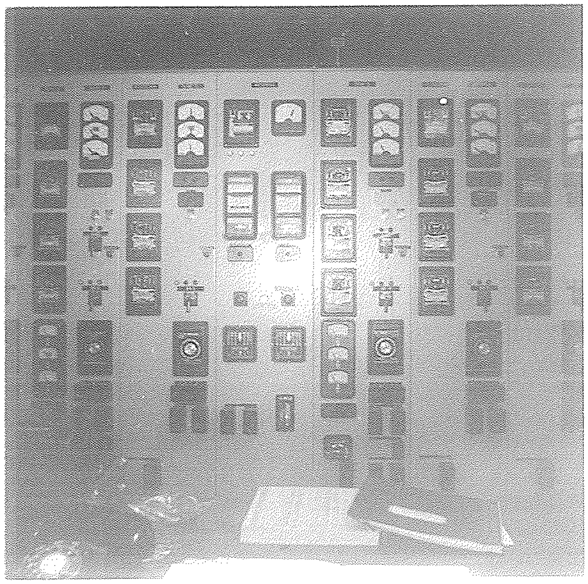


Fig. 18

Metering and Relaying at Brandon (66 kV)

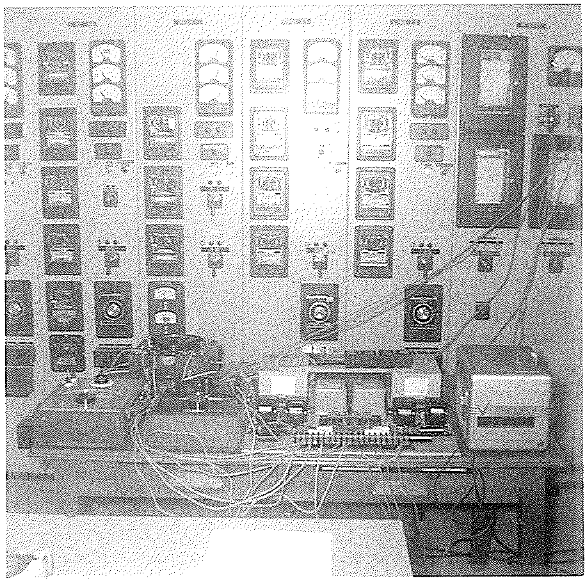


Fig. 19

Metering Relaying, and Recording Setup at Brandon (33 kV)

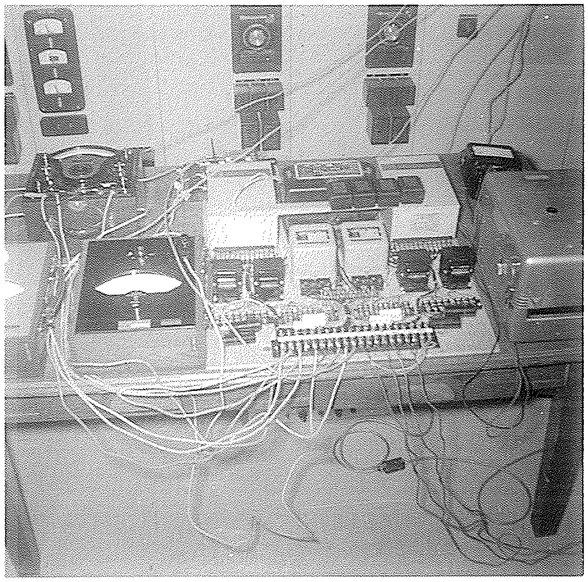


Fig. 20

Instruments, Transducers and Power Supplies at Brandon (33 kV)

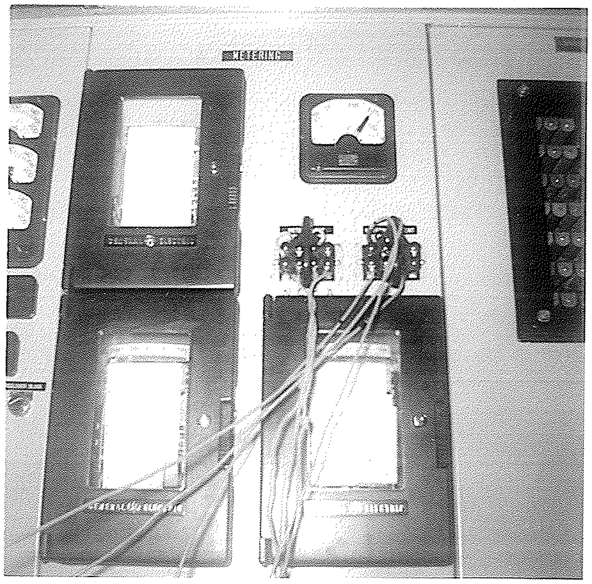


Fig. 21

Metering at Brandon (33 kV)

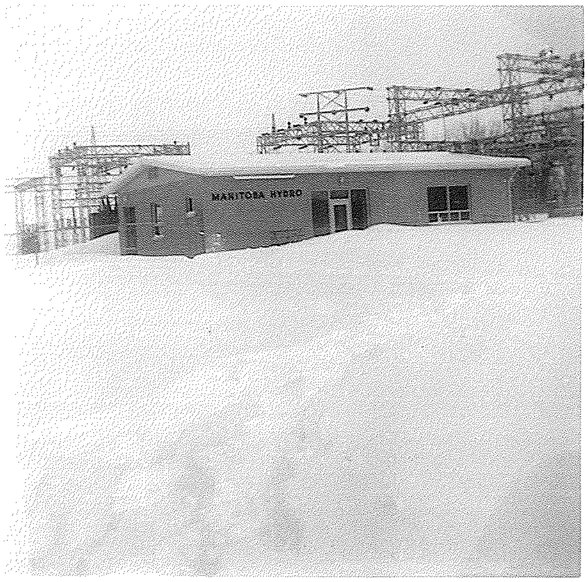


Fig. 22

Rosenfeld Station and
Control Building

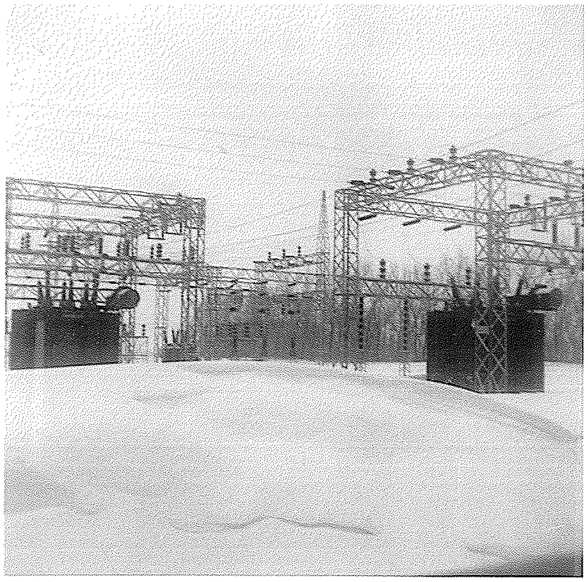


Fig. 23

Rosenfeld Station

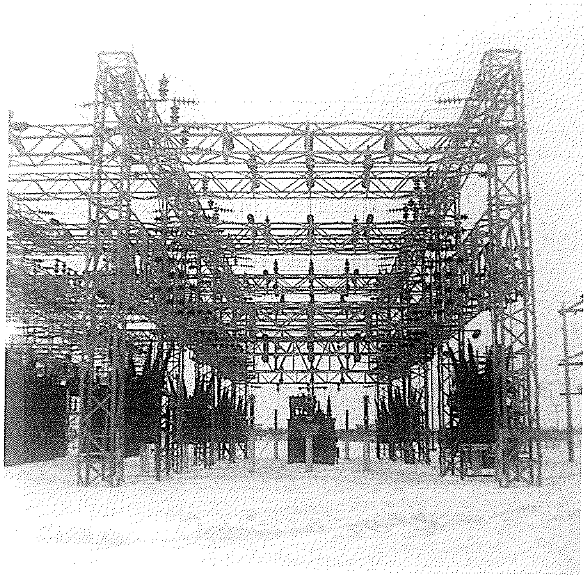


Fig. 24

Neepawa Station

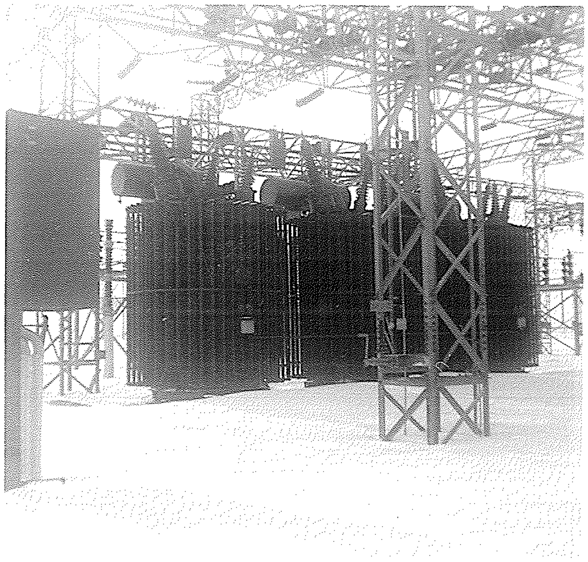


Fig. 25

Transformers at Neepawa

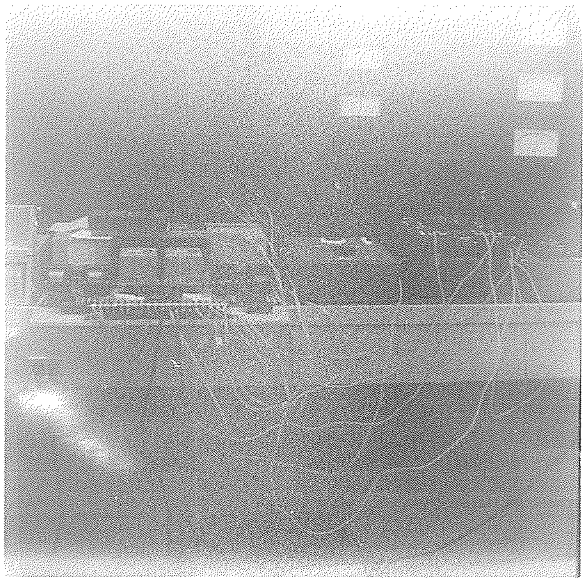


Fig. 26

Recording Setup

at Neepawa

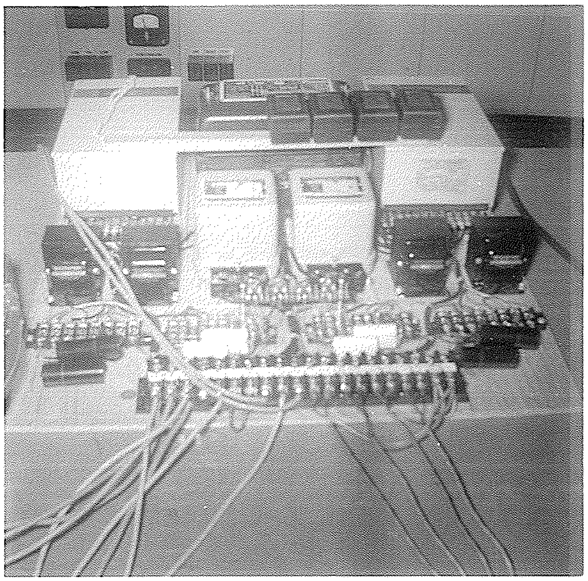


Fig. 27

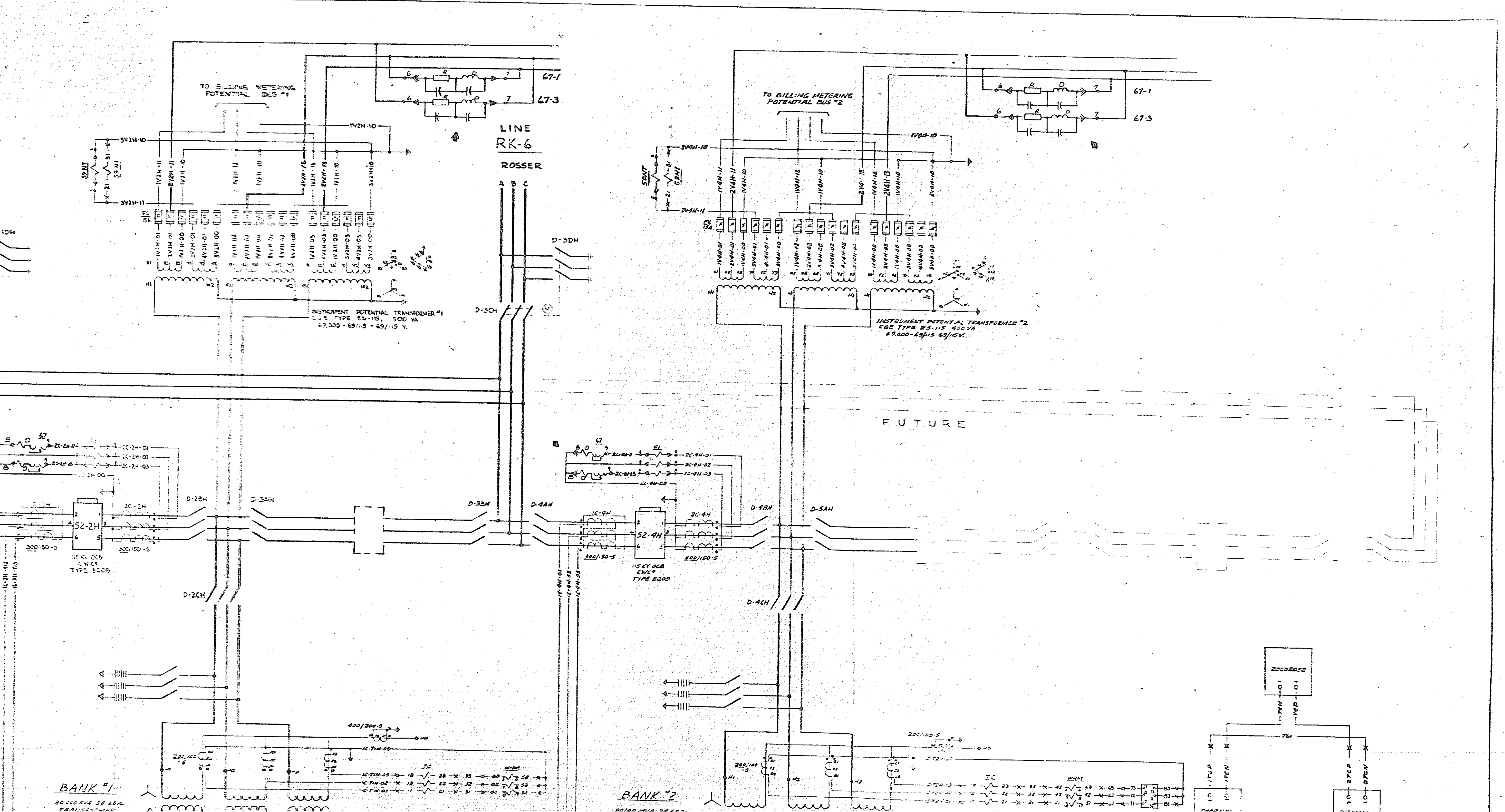
Transducers and

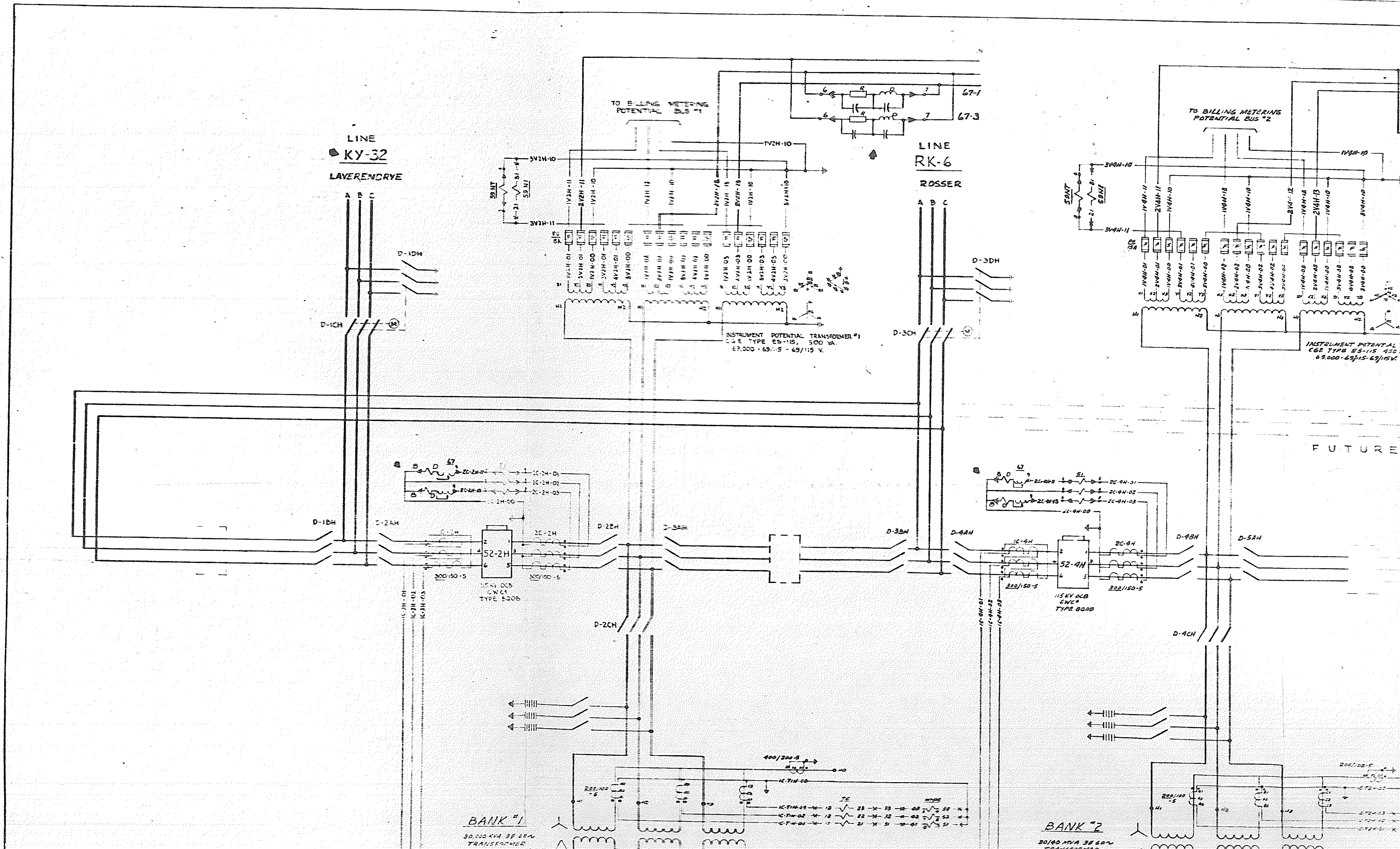
Power Supplies

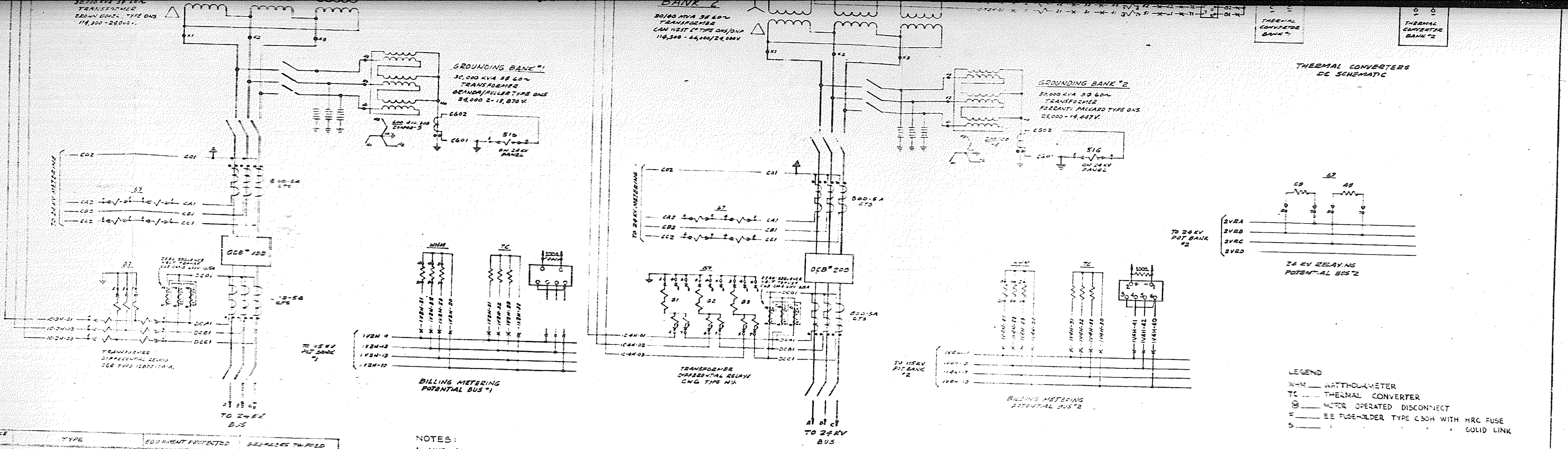
at Neepawa

APPENDIX E

Sample of Single - Line Diagram


TO BILLING METERING POTENTIAL BUS #1
3V2H-10
3V2H-11
59 NT
59 NI
1V2H-10
1V2H-11
2V2H-11
2V2H-13
3V2H-10
6
R
D
7
67-1
67-3
LINE
RK-6
ROSSER
A
B
C
D-3DH
D-3CH
H1
H2
INSTRUMENT POTENTIAL TRANSFORMER #1
CGE TYPE ES-115, 500 VA.
69,000 - 69/115 - 69/115 V.
TO BILLING METERING POTENTIAL BUS #2
1V4H-10
3V4H-10
3V4H-11
59NT
59NI
1V4H-11
2V4H-11
2V4H-12
2V4H-13
3V4H-10
INSTRUMENT POTENTIAL TRANSFORMER #2
CGE TYPE ES-115 400 VA
69,000-69/115-69/115V.
FUTURE
67
2C-2H-01
2C-2H-02
2C-2H-03
2C-2H-00
1C-2H
52-2H
2C-2H
300/150-5
115 KV OCB
CWC°
TYPE 8Q0B
D-2BH
D-3BH
D-2CH
D-3AH
D-4AH
2C-4H-01
2C-4H-02
2C-4H-03
2C-4H-00
1C-4H
52-4H
2C-4H
300/150-5
115 KV OCB
CWC°
TYPE 8Q0B
1C-4H-01
1C-4H-02
1C-4H-03
D-4BH
D-5AH
D-4CH
400/200-5
200/100-5
1C-T1H-00
1C-T1H-03
1C-T1H-02
1C-T1H-01
TC
WHM
BANK #1
30,000 KVA 3Ø 60~
TRANSFORMER
BANK #2
30/40 KVA 3Ø 60~
200/100-5
H1
H2
H3
RECORDER
TCI
1TCP
1TCN
2TCP
2TCN
THERMAL
THERMAL


LINE
KY-32
LAVERENDRYE
A B C
D-1DH
D-1CH
D-1BH
D-2AH
1C-2H
52-2H
2C-2H
300/150-5
115 KV OCB
CWC°
TYPE 8Q0B
1C-2H-01
1C-2H-02
1C-2H-03
67
D
2C-2H-01
2C-2H-02
2C-2H-03
2C-2H-00
D-2BH
D-2CH
D-3AH
D-3BH
TO BILLING METERING
POTENTIAL BUS #1
3V2H-10
3V2H-11
59NT
59NI
1V2H-11
2V2H-11
1V2H-10
1V2H-13
2V2H-13
3V2H-10
FU
15A
INSTRUMENT POTENTIAL TRANSFORMER #1
CGE TYPE ES-115, 500 VA
69,000 - 69/115 - 69/115 V.
H1
H2
6
R
7
67-1
67-3
LINE
RK-6
ROSSER
D-3DH
D-3CH
FUTURE
D-4AH
1C-4H
52-4H
2C-4H
300/150-5
115 KV OCB
CWC°
TYPE 8Q0B
1C-4H-01
1C-4H-02
1C-4H-03
67
51
2C-4H-01
2C-4H-02
2C-4H-03
2C-4H-00
D-4BH
D-5AH
D-4CH
TO BILLING METERING
POTENTIAL BUS #2
3V4H-10
3V4H-11
59NT
59NI
1V4H-11
2V4H-11
1V4H-10
1V4H-13
2V4H-12
2V4H-13
3V4H-10
1V4H-10
FU
15A
INSTRUMENT POTENTIAL
CGE TYPE ES-115 400
69,000-69/115-69/115V.
400/200-5
1C-T1H-00
200/100
-5
TC
1C-T1H-03
1C-T1H-02
1C-T1H-01
BANK #1
30,000 KVA 3Ø 60~
TRANSFORMER
200/100
-5
H1
BANK #2
30/40 MVA 3Ø 60~
200/100-5



LEGEND
WHM ____ WATTHOURMETER
TC ____ THERMAL CONVERTER
Ⓜ ____ MOTOR OPERATED DISCONNECT
F ____ EE FUSEHOLDER TYPE C30H WITH HRC FUSE
S ____ " " " " " SOLID LINK

TYPE	EQUIPMENT PROTECTED	BREAKERS TRIPPED
CGE ACB3A1A OVERCURRENT	BANK #2	52-2H
CGE IAV51A1A TIME OVERVOLTAGE	LINES KH-88 KK-6	52-6H
CGE IBCG51A DIR TIME OVERCURR	BANK #2	24KV BKR #220
CHG HU TRANSF DIFFER.	BANK #2	52-4-2 BKR #200
CGE PJV11A INST OVERVOLTAGE	LINES KH-88 KK-6	52-6H
CGE IAC53A GROUND OVERCURR	BANK #2	52-4H BKR #200

NOTES:

1. -LINE DISC WITH GROUND BLADES (D-1CH & D-10H, D-3CH & D-30H) ARE E.P.D. TYPE TTR-A, 115 KV 600A, WITH QUICK BREAK HORN AND MOTOR MECHANISM.
   - BANK DISC D-3CH & D-4CH ARE TYPE TTR A, 600 A, VERTICAL LIFT.
   - SELECTOR DISC ARE TYPE A SPECIAL SIDEBREAK SWITCHES, 1200A. (D-1BH, D-2AH, D-2BH & D-3AH, D-3BH D-4AH D-4BH & D-5AH
2. -ALL SYMBOLS & DEVICE FUNCTION NUMBERS ARE IN ACCORDANCE WITH A.S.A. STANDARDS Y32.2 & 37.2, UNLESS SHOWN IN LEGEND

REFERENCE	DRAWING NO.
1407-D-8211	115 KV CONTROL & RELAY SWITCHBOARD PANEL #2 WIRING DIAG.
1407-E-8014	RELAY & BUS SCHEMATIC
1407-B-6402	MRC. BANK #1 CONTROL HOUSING, CONNECTION DIAGRAM
1407-E-8203	115 KV CONTROL & RELAY SWBD FULL WIRING DIAGRAM
1407-C-8202	115 KV POT TRANS. CONNECT & FUSE BOX, WIRING DIAGRAM
1407-5-100	CWC# 19L863 5205 MO OCB. WIRING DIAGRAM
1407-D-6406	115 KV SW STRUCT. OCB CONT CABLES CONNECTION DIAGRAM
1407-D-6201	BILLING METERING PANEL, WIRING DIAGRAM
1407-D-7001	SINGLE LINE DIAGRAM

	No.	REVISION	BY	
[illegible]	7	ADDED DEVICE 67-1, 67-2 (TIME DELAY) WO 137-3	GE	
[illegible]	6			
[illegible]	5	CHANGED METERING C.T. RATIOS		
[illegible]	4	ADDED GROUND TO HU RELAYS BANK 2	LC	
[illegible]	3	ADDED BANK #2, POT TRANSF #2 & ASSOCIATED EQUIPMENT	LC	
[illegible]	2	CHANGED OVERVOLTAGE RELAY DESIGNATIONS	H.A.	JHB
[illegible]	1	GROUNDED POT.TRANS. "Y" WINDING	H.A.	JHB

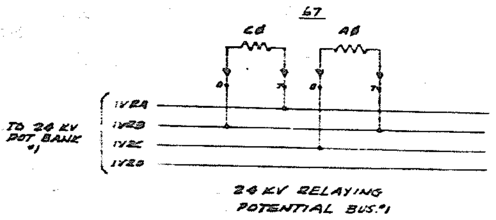
DRAWN	H.A.
CHECKED	JHB
NOTED	
CIVIL	
ELECT.	—
MECH.	
CONST.	
APPROVED	

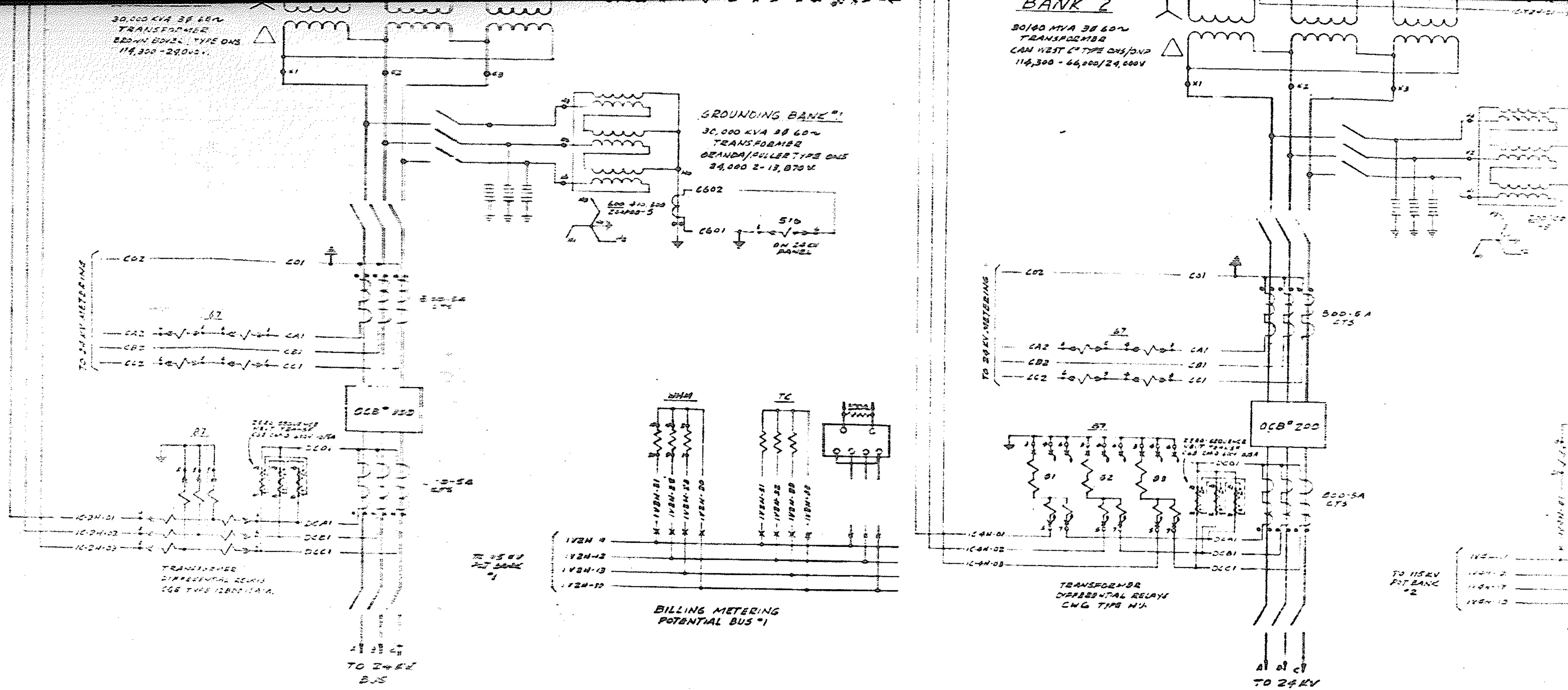
THE MANITOBA HYDRO-ELECTRIC BOARD
OPERATING WINNIPEG ELECTRIC COMPANY
ENGINEERING & CONSTRUCTION DIVISION

RAEFIELD PARK STATION

KV SWITCHING STRUCTURE
SCHEMATIC DIAGRAM

DRAWING No.
1407 - E - 6004 | 7





APPARATUS	LOCATION	MFR.	TYPE
T.C.	BANK #1 & #2	SANGAMO	C-W15M
WHM	BANK #1 & #2	C.G.E.	DS-44

DEVICE Nº	TYPE	EQUIPMENT PROTECTED	BREAKERS TRIPPED	DEVICE Nº	TYPE	EQUIPMENT PROTECTED	BREAKERS TRIPPED
51	C.G.E. IAC53A, OVERCURRENT	BANK #1	52-2H	51	CGE IAC53A/M OVERCURRENT	BANK #2	52-2H
59NT	C.G.E. IAV51 A, TIME OVERVOLTAGE	LINES A-B & RK-6	52-2H	59NT	CGE IAV51A/M TIME OVERVOLTAGE	LINES A-B & RK-6	52-2H
67	C.G.E. IBC53 A2A, DIR. TIME OVERCURR.	BANK #1	24KV BKR #100	67	CGE IBC53M/A DIR TIME OVERCURR	BANK #2	24KV BKR #200
87	C.G.E. BDD 5A, TRANSF. DIFFER.	BANK #1	52-2H, BKR #100	87	CWG HU TRANSF DIFFER	BANK #2	52-2H & BKR #200
59NI	C.G.E. PJV 11A, INST. OVERVOLTAGE	LINES A-B & RK-6	52-2H	59NI	CGE PJV11A/L INST OVERVOLTAGE	LINES A-B & RK-6	52-2H
64G	CGE AC53B4A GROUND OVERCURR	BANK #1	52-2H & BKR #100	64G	CGE AC53A/M GROUND OVERCURR	BANK #2	52-2H & BKR #200

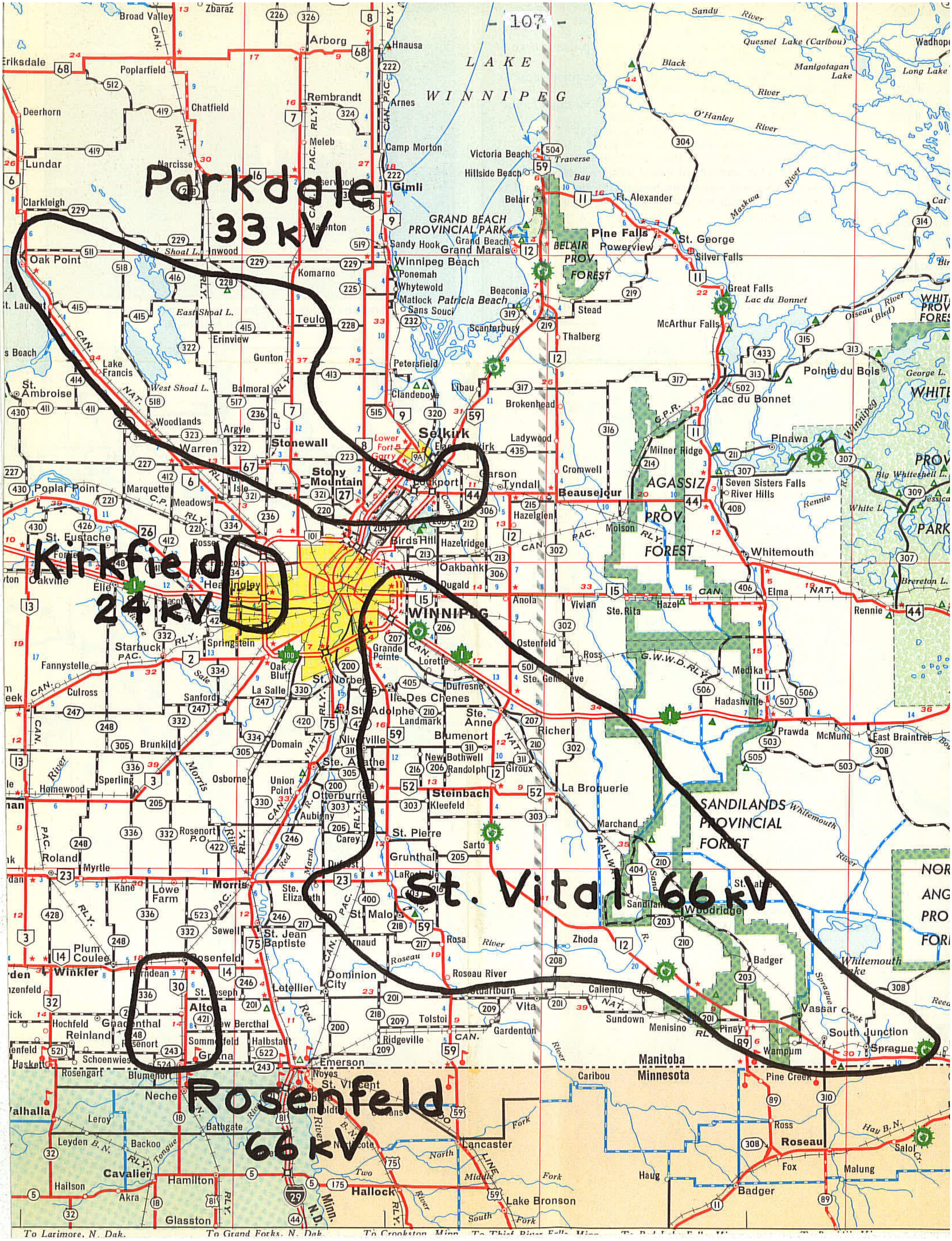
NOTES:

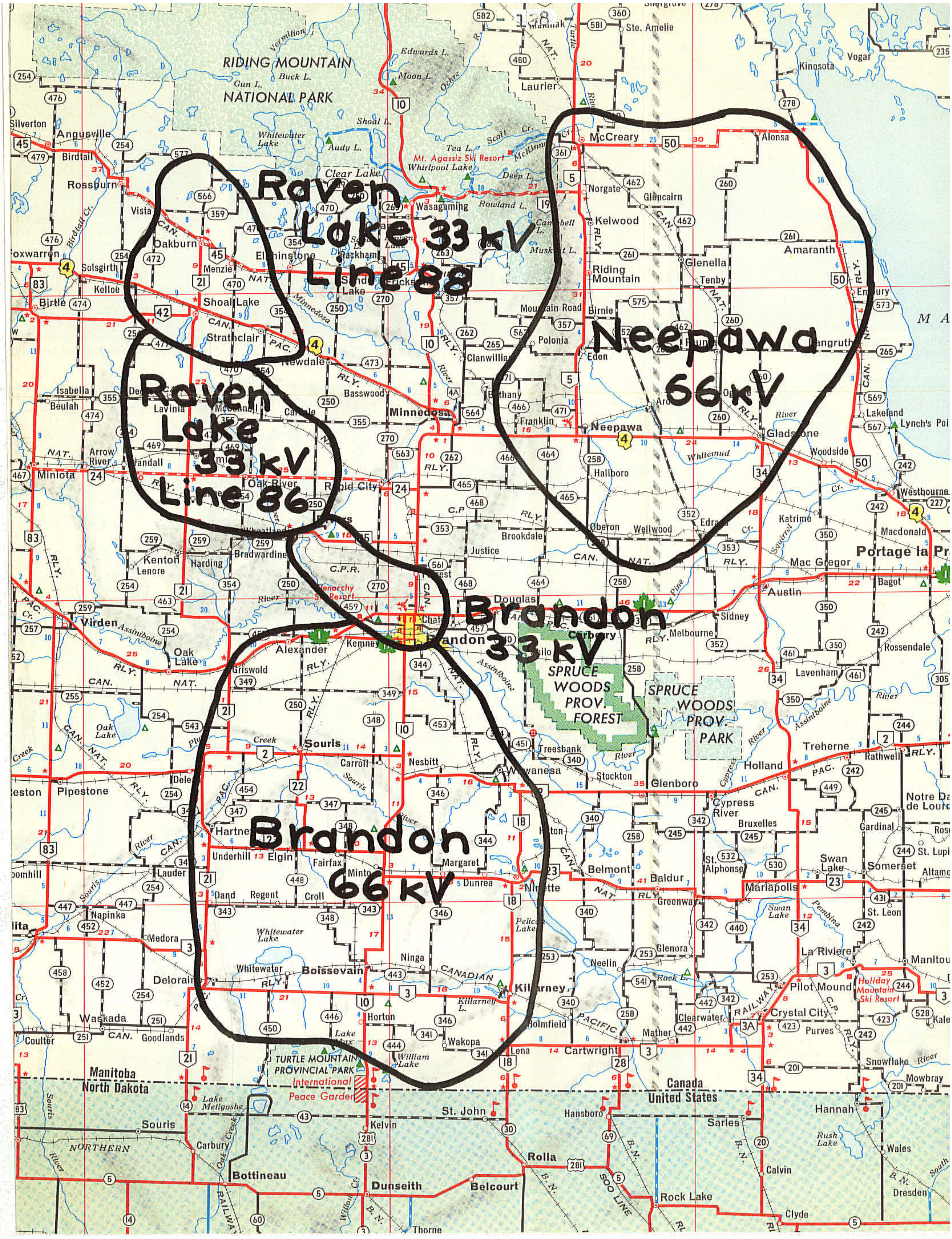
1. -LINE DISC WITH GROUND BLADES (D-1CH & D-1DH, D-3CH & D-3DH) ARE E.D.D. TYPE TTR-A 115 KV 600A, WITH QUICK BREAK HORN AND MOTOR MECHANISM
   - BANK DISC (D-2CH & D-4CH) ARE TYPE TTR A, 600 A, VERTICAL LIFT.
   - SELECTOR DISC ARE TYPE A SPECIAL SIDEBREAK SWITCHES, 1200A (D-1BH, D-2AH, D-2BH & D-3AH, D-3BH, D-4AH, D-4BH & D-5AH
2. -ALL SYMBOLS & DEVICE FUNCTION NUMBERS ARE IN ACCORDANCE WITH A.S.A. STANDARDS Y32.2 & 37.2, UNLESS SHOWN IN LEGEND

1407-D-8211	115 KV CONTROL & RELAY SWITCHBOARD PANEL #2 [illegible]
1407-E-8014	RELAY & BUS SCHEMATIC
1407-B-8402	MRC. BANK #1 CONTROL HOUSING, CONNECTION DIAGRAM
1407-E-8203	115 KV CONTROL & RELAY SWBD. FULL WIRING DIAGRAM
1407-C-8202	115 KV POT TRANS., JUNCT. & FUSE BOX, WIRING DIAGRAM
1407-5-100	CWC# 19(865) 5205 MO OCB, WIRING DIAGRAM
1407-D-8404	115 KV SW STRUCT., OCB CONT CABLES CONNECTION DIAGRAM
1407-D-8201	BILLING METERING PANEL, WIRING DIAGRAM
1407-D-7001	SINGLE LINE DIAGRAM
REFERENCE	DRAWINGS

APPENDIX F

Geographic Areas Tested


Parkdale
33 kV
Kirkfield
24 kV
St. Vital 66 kV
Rosenfeld
66 kV
LAKE WINNIPEG
WINNIPEG
Selkirk
Stonewall
Steinbach
Morris
Altona
Emerson
Manitoba
Minnesota
SANDILANDS PROVINCIAL FOREST
AGASSIZ PROV. FOREST
To Larimore, N. Dak.
To Grand Forks, N. Dak.
To Crookston, Minn.


Raven Lake 33 kV Line 88
Raven Lake 33 kV Line 86
Neepawa 66 kV
Brandon 33 kV
Brandon 66 kV
RIDING MOUNTAIN NATIONAL PARK
SPRUCE WOODS PROV. FOREST
SPRUCE WOODS PROV. PARK
TURTLE MOUNTAIN PROVINCIAL PARK
International Peace Garden
Manitoba
North Dakota
Canada
United States
McCreary
Alonsa
Amaranth
Neepawa
Gladstone
Portage la Prairie
Minnedosa
Brandon
Souris
Boissevain
Killarney
Virden
Shoal Lake
Birtle
Russell
Rivers
Carberry
Glenboro
Wawanesa
Deloraine
Melita
Bottineau
Rolla
Dunseith
Belcourt

APPENDIX G

Letter

X1-1910

MANITOBA HYDRO

INTER-OFFICE MEMORANDUM

From W. J. Tishinski
Transmission Planning Engineer
System Planning Division

To Mr. C. J. Goodwin, Manager
Electrical Planning Department
System Planning Division

File No. 2-1A1-4

Date April 15, 1968

Subject LOAD TESTS UNDER STEP VOLTAGE CHANGES.

The recent tests which were taken at Harrow Station to determine load behaviour under transient conditions were reviewed and analyzed.

Three methods used to represent loads at present are:

1. Constant impedance
2. Constant current
3. Constant power

In the first case the current varies directly as the voltage and the power varies as the square of the voltage.

In the second case the current is constant and the power varies directly as the voltage.

In the third case the current varies inversely ~~as the square of~~ as the voltage and the power is constant.

The tests taken at Harrow showed that the current varied approximately as the 5th power of the voltage and the power varied approximately inversely as the 3rd power of the voltage.

Since in an actual system there is a combination of the 3 types of basic loads the power and current should (as has been proven by tests done by other people) varied somewhere between the 1st and 2nd power of the voltage. The power of 1.6 has been used quite often in literature.

Comparing our results with what theoretically should have happened we can only conclude that either something was fundamentally inaccurate with the method the tests were carried out or the metering or test equipment was not adequate.

Off hand, it would appear that the step voltage change was not great~~er~~ enough to cause sufficient meter deflection. When tests are carried out at Parkdale, where we feel we can obtain greater voltage changes, this factor should be eliminated.

VJS/cr

cc: Mr. F. A. Jost

APPENDIX H

Description of Stations

DESCRIPTION OF STATIONS

Kirkfield Terminal Station

The Kirkfield Terminal Station is situated on Saskatchewan Avenue in Winnipeg just west of the Perimeter Highway immediately north of the Assiniboia Racetrack.

The Terminal Station is supplied from a double circuit 115 kV line between the Rosser and the La Verendrye Stations. Only one of the two circuits is tapped. The 115 kV bus is designed to operate ultimately as a ring. In the meantime the bus is operated radially with a circuit breaker on each of the two banks only.

The two power transformers in the station transform the voltage from the 115 kV level to the sub-transmission 24kV. Each bank has a self cooled rating of 30 MVA. Bank 2 is also equipped with fans to provide a forced rating of 40 MVA.

The Station has a 24 kV radial bus with five 24 kV lines leaving the station. An 8.4 MVAR capacitor bank is installed with load current control and voltage override.

The 24 kV circuits supply a number of stations in the St. James - Assiniboia area of Winnipeg and are networked into the McPhillips, Harrow, and Mohawk 24 kV supplies.

Since the Kirkfield Station is one of the stations on the Manitoba Hydro System which are networked with other sources it was necessary to open the network at key locations.

Without the opening of the looped system any tendency for voltage to change at the Kirkfield supply would cause a greater amount of VARs to flow from the other stations. This would tend to maintain voltages at their previous levels as well as change the reactive power flows. There would be small changes in real power flows as well. It is hard to generalize but essentially the amount of real power supplied from each station would depend on the relative impedances connected beyond the looped stations and the load. The problem is overcome by isolating loads so that they are supplied by only one station.

Because of switches which are normally kept open for protection and reliability reasons it was possible to isolate the Kirkfield Station by opening only two 24 kV circuit breakers at the St. James Station.

St. Vital Station

The St. Vital Terminal Station is located near the southeastern edge of the City of Winnipeg on P.T.H. 59 south of the Trans Canada Highway.

The terminal station is supplied by a network of many lines from Selkirk Generating Station and Transcona, Harrow, and Mohawk Terminal Stations. The Terminal Station provides a supply both to the 24 kV and 66 kV sub-transmission systems. The 66 kV sub-transmission system supplying the south-eastern part of Manitoba was used in the tests.

The 115 kV switchyard at the St. Vital Station is in the form of a double bus arrangement with one supplying all elements and the auxiliary bus normally energized through a bus-tie breaker acting as standby. The supply to the 66 kV system is from 2 - 30/40 MVA power transformers.

The 66 kV bus at the St. Vital Station is in the form of a ring. For switching purposes two circuit breakers had to be opened to trip a transformer. This could have been accomplished by tripping a high side breaker, however this was not done because of the systems dispatchers' preference to do switching on the low side of transformers. There are no capacitor banks on the 66 kV bus, however, there is an 8.4 MVAR bank on the 24 kV bus, again with load current control and voltage override.

The 66 kV system at St. Vital supplies the area from Dugald east to St. Anne south to Sprague and west to the Red River. There are tie-lines to adjacent systems, however these are normally operated open and therefore there was no need to isolate any of the system.

Parkdale Terminal Station

The Parkdale Station is one of the older stations in Manitoba situated on P.T.H. 8 north of the Winnipeg perimeter highway.

Parkdale is supplied at 115 kV by two lines from Pine Falls, and two from Great Falls Generating Station via the Mapleton Substation and the Selkirk Generating Station. The station serves as main supply point at 115 kV with two lines emanating to Neepawa, one to Portage la Prairie, and two to Rosser.

As well as 115 kV the Parkdale Station supplies a 66 kV area and a 33 kV area. Both of these sub-transmission voltages are confined primarily to the Interlake Area. The 66 kV also supplies portions of the northern outskirts of the City of Winnipeg.

Because the 33 kV system supplies only the Interlake area it was decided to record the characteristics of this load.

The switching arrangement at the Parkdale Station is diversified in that each voltage level is different. The 115 kV has a unique folded ring while the 66 kV bus is a classical double bus arrangement. The 33 kV supply on the other hand has a radial bus supplying two other separately regulated radial busses. This arrangement permits the supply of two distinct areas with different voltage levels.

The supply to both sub-transmission voltages is by means of four 15/20 MVA dual-voltage power transformers. The 66 kV winding has the same rating as the transformer while the 33 kV is only rated at 5/6.67 MVA.

Again as at St. Vital the low side circuit breakers were used for switching. There are no capacitors at Parkdale for power correction or voltage control.

Rosenfeld Station

The Rosenfeld Terminal Station is located near the town of Rosenfeld which is on P.T.H. 14 between Letellier and Morden.

Rosenfeld is supplied by two 115 kV circuits from the La Verendrye Station -- one direct and the other via Morden Corner. The 115 kV switching arrangement has recently been modified into a ring arrangement.

The 115 kV supplies both a sub-transmission 66 kV and 33 kV system with 2 - 15/20 MVA transformers identical to the units at Parkdale.

Both the 33 kV and 66 kV busses at Rosenfeld are radial, however both sub-transmission systems are interconnected with adjacent terminal stations. Because of this it was necessary to first isolate Rosenfeld from any other source in order not to mask the load behaviour by VAR transfers from other sources.

The Rosenfeld supply area is confined to the Letellier - Morden area with a major load at the Interprovincial Pipeline Gretna Pumping Station. This is almost all composed of large induction motors and as such is very interesting as far as transient load response is concerned. Since these large motors are supplied by the 66 kV this supply was chosen for the tests at Rosenfeld.

There are no capacitors at the Rosenfeld Station, however, a bank is permanently installed to the terminals of each motor at the pumping station for power factor correction.

Brandon - 17th Street East Station

The Brandon - 17th Street East Station is located at the intersection of Victoria Avenue and 17th Street East on the eastern outskirts of the City of Brandon. The Brandon Generating Station is situated about 1 mile further east and this is the supply point of the 17th Street East Station via 3 - 115 kV circuits.

It was decided to take tests at this station for several reasons. One of these was that it was possible to monitor two distinct loads. One of these the 33 kV system which has some outlying load, however, is confined almost entirely to the City of Brandon area. Because of the size of the load compared to the rest of the loads in the western part of the province and its unique nature — basically an urban area, it was decided to record this load independently.

The second load which is supplied by the Brandon - 17th Street East Station is the 66 kV system. This area is basically the rural area beyond the immediate City of Brandon vicinity which is served by the 33 kV. The load is characteristically rural, farms both small and large as well as small and larger rural towns. There is also an Interprovincial Pipeline Pumping Station served by this system, however the load is small compared to other pumping stations because large motors at this station are supplied by the 230 kV system.

There was no need to isolate either the 33 kV or 66 kV supplies from other terminal stations as these are normally operated radially.

The 66 kV bus arrangement at the Brandon - 17th Street East Station is in the form of a ring. Switching was performed by first opening a low side circuit breaker adjacent to a transformer bank thereby splitting the ring. The second step was to open a second circuit breaker on the opposite side of the transformer to the one that was already open.

The 33 kV bus at this station is a standard radial scheme with one breaker on each element. This makes it easy in that only one circuit breaker need be opened to disconnect a transformer bank. The 33 kV at this station was of more interest than normal because of the three transformers which are located there. Two of these are 15 MVA units and one is a 30 MVA unit. Because of unequal rating and the fact that the transformers have essentially the same impedance on their own base several step changes in impedance and therefore voltage are possible.

There are no capacitor banks at the Brandon - 17th Street East Station, however numerous banks exist on the distribution system. No attempt was made to control these during the tests.

Raven Lake Station

Raven Lake Station is located four miles south of Shoal Lake along P.T.H. 21. This station is supplied by two 115 kV transmission lines. One line comes from Neepawa via Minnedosa, while the second one is an express circuit from the Dauphin-Vermilion Station. A third 115 kV line continues west to supply the Birtle area and to loop south to Virden.

The supply to the 33 kV sub-transmission system at Raven Lake is by a 15 MVA and 7.5 MVA bank operated in parallel. The bus configuration on the sub-transmission supply is radial.

It was not possible to take readings directly from the banks because two different current transformers were in use and adding these would give a meaningless result. It was therefore decided to record the loads on two independent 33 kV sub-transmission circuits. The loads on the lines were much smaller than previous measured loads, however it was felt the area south of Riding Mountain National Park supplied by Raven Lake was quite unique and worthy of study.

Because of the different size of the two transformers it was possible to get two different voltage changes. It, however, was found that both changes were small.

The Raven Lake load area is mainly of a rural nature.

Neepawa Station

Neepawa Station is located east of the town of Neepawa along P.T.H. 4. This station has two 115 kV supply lines from the Parkdale Station with one outfeed line to Minnedosa and then to Raven Lake. A fourth line connects with the Brandon Generating Station which acts as an outfeed or infeed line depending on whether Brandon Generating Station is on or not.

The 115 kV bus at the Neepawa Station is in the form of a ring with two elements being 15 MVA transformers supplying a radial 66 kV bus.

All 66 kV lines out of the Neepawa Station are normally operated radial except the tie-line to Minnedosa which is looped in. In order not to get any false readings this tie was opened at Minnedosa prior to the commencement of the tests.

The Neepawa area load consists of small and medium sized rural towns as well as a good farming area.

APPENDIX I

List of Equipment Used in Tests

List of Equipment Used in Tests

1. Cambridge Ammeter (RM 12)
   0.5/1/2/5/10 amp - Serial L399447

2. Cambridge Voltmeter (RM 7)
   7.5/15/30/75/150 volt - Serial 1404730

3. General Electric Poly-Wattmeter (RM 18)
   Type P3, 5/10 amp 150 volts - Serial 578648

4. Honeywell Visacorder (RM 90)
   24 channel, model 1508AT2A670JL00

5. Simpson Multimeter (RM 24)
   2.5/10/50/250/1,000 volts - Type 270
   500/100/10/1 ma 1/100/10,000 ohms

6. Landis & Gyr Current Transducer
   Type F1C21
   output 5 ma - rating 5 amps

7. Landis & Gyr Voltage Transducer
   Type F1C2E
   output 5 ma - rating 115 volts

8. General Electric Watt Transducer
   Type 4701 AC watts to DC 3ϕ 3w
   rating 500 watts
   output 1 ma DC into 4400 ohms

9. General Electric Watt Transducer (used as VAR tranducer)
   Type 4701 AC watts to DC 3φ 3w
   rating 500 watts
   output 1 ma DC into 4400 ohms

10. VAD Phase Shifting Transformer
    115 volts 3φ 4w 60 Hz

11. 4 - Hammond 193C Chokes

12. 4 - Honeywell Galvanometers
    Series M - sub-miniature, Type No. M3300
    Fluid damped

13. Sorensen AC Regulator - model 1001 - RM 243

14. 4 - variable resistors (500 ohms)

15. 2 - 240 ohm resistors

16. 2 - 910 ohm resistors

17. 8 - 3300 ohm resistors

18. 8 - 10 μf capacitors

19. Test Board

20. 4 - Jana AC Adapters - model JJ - 10508
    input 117 volts - 50/60 c/s - 5 watts
    output 9 volts - 250 ma

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