DEVELOPMENT OF THE LOAD TAP CHANGING TRANSFORMER CONTROL CIRCUIT IN PREPARATION FOR PARALLELING

by

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INTRODUCTION

This thesis records the progress of certain phases in the development of the load tap changing transformer manufactured by the Wagner Electric Corporation. The thesis is divided into three parts entitled, (I) "The LTC Control Circuit", (II) "The Line Drop Compensator Circuit", and (III) "Paralleling Considerations".

The Wagner LTC control was designed primarily for use with power transformers of above the 1000-kva range. In brief, the magnetic amplifier control replaces the voltage regulating relay approach in initiating the signal for tap change under conditions of under or over voltage in the transformer load circuit.

For the most part, curves and data obtained by experiment are grouped together in the Appendix as are most of the calculations. These are referred to from time to time in the body of the thesis.

It will be noted that most of the improvements which were made were aimed primarily toward preparing the unit for paralleling satisfactorily with other units. Of course, other improvements appear as by-products of this study.

With respect to the improvements in the control circuit itself, circuit changes are summarized at the end of Part I. Part II then follows through some changes made in the line drop compensator as well as a proposal for several other possible changes which could be made at a future date should these changes prove feasible from the standpoint of space and economics.

Part III deals with some of the necessary considerations in the parallel operation of load tap changing transformers. The goal of this particular phase of the thesis is not the detailed development of any one paralleling circuit. Most paralleling circuits will vary considerably, depending upon the manufacturers of the transformers to be paralleled and the paralleling method that is chosen. The purpose of Part III is to bring together information concerning these various paralleling methods, pointing some advantages and disadvantages of each. This part of the thesis could serve as a general guide to the engineer who is faced with the job of adapting one or more of the Wagner units for paralleling with others.

Several abbreviations which are often used throughout this thesis may be confusing because of their similarity. Therefore they are defined as follows:

LTC = load tap changing transformer

LDC = line drop compensator

LCT = load current transformer, sometimes referred to as a blocking current transformer

CCT = compensating current transformer, also called an equalizing current transformer.

PART I. THE LTC CONTROL CIRCUIT

Operation of the "Original" Circuit

<u>Principle</u> <u>of</u> <u>Operation</u>. The diagram sheet, TE8778B, is a

schematic of what will be referred to as the "original" control circuit. By this it is meant that TE8778B, Fig. 36, is the circuit on which improvement is to be made, as explained in this thesis. To further simplify the brief discussion on the theory of operation of the "original" circuit, a block diagram is shown in Fig. 1.

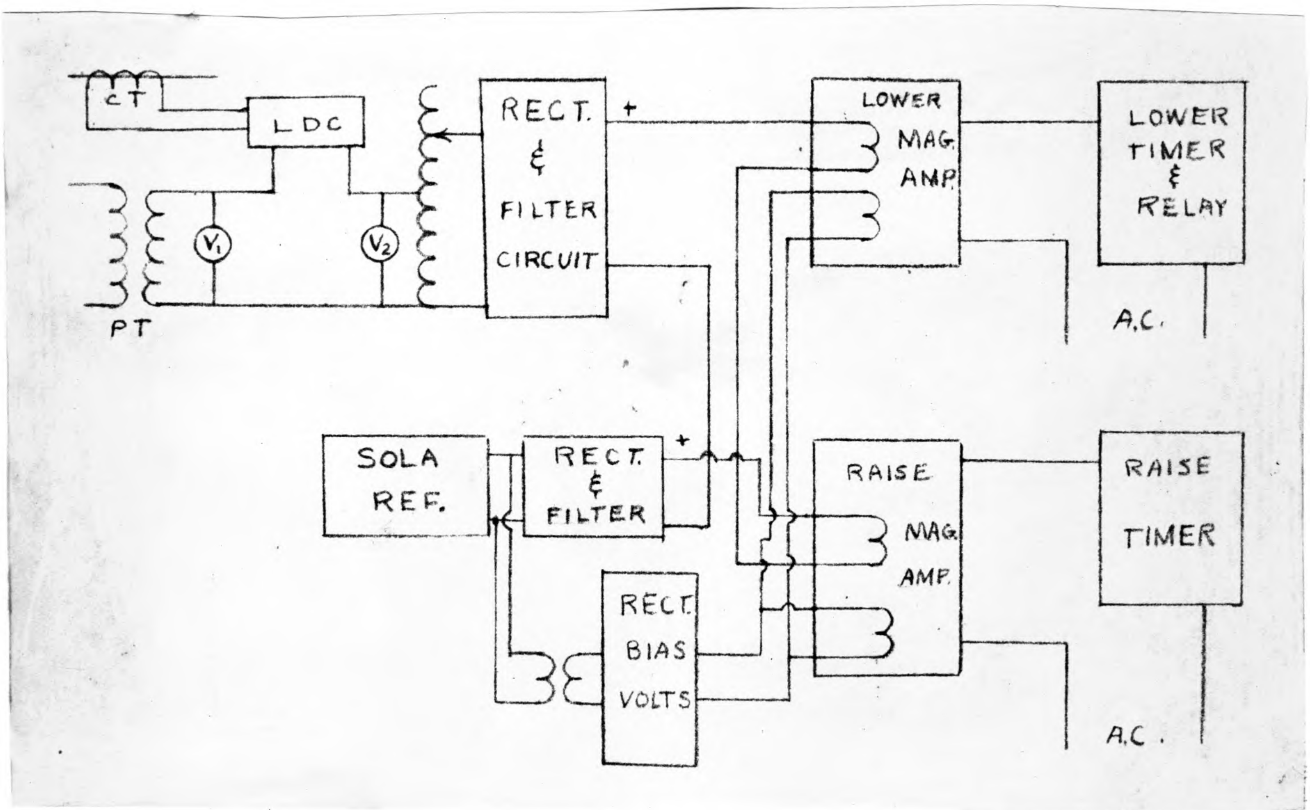


Fig. 1.

The object of the LTC (load tap changer) control circuit is, of course, to automatically initiate a tap change on the main transformer whenever the customer load voltage varies from some established reference voltage for a predetermined period of accumulated time. Viewing the block diagram (Fig. 1), the potential transformer (PT) is located at the secondary of the main transformer. Briefly, the customer's load voltage is dependent upon two things: (1) The voltage at the main transformer secondary, and (2) the IZ drop of the transmission line. Since both the sensing equipment and the tap-changing mechanism are located at the main transformer, the line drop compensator (LDC) is necessary to serve as a representation of the line. (See Fig. 2.)

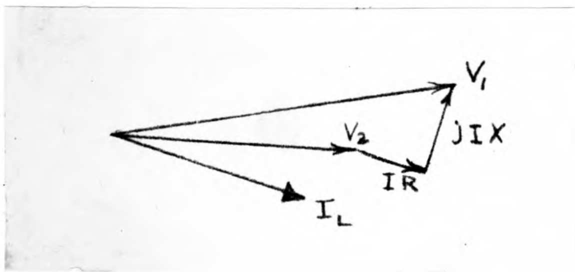


Fig. 2a.

$\overline{V}_2 = \overline{V}_1 + \overline{I}_L Z_{line}$

$\overline{V}_2$ = customer load voltage

$\overline{V}_1$ = main transformer secondary voltage

I_L = line current

Z = line impedance

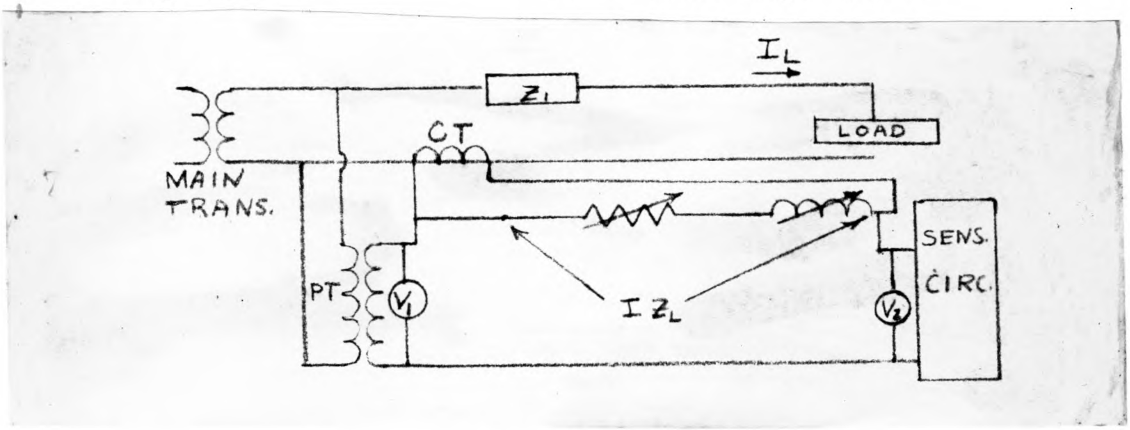


Fig. 2b

A simplified version of the LDC is shown in Fig. 2b. Here it is seen that the current transformer (CT) along with the variable Z_L serves to simulate the voltage drop of the line.

The alternating-current voltage (V_2) is then fed into the sensing circuit to be rectified, filtered, and then compared with a rectified filtered reference voltage, the latter being held constant. This voltage comparison is made by connecting the sensing and reference output voltages in opposition through the control windings of the raise and lower magnetic amplifiers, as shown in Fig. 1. The magnetic amplifiers of this circuit are used as bi-stable switching devices which are either in the saturated or unsaturated condition with respect to the magnetic core. When in the unsaturated state, the a-c load winding of the magnetic amplifier shows high impedance to any current ($L = N \frac{d\phi}{dI}$). When in the saturated state, the current is sufficient to operate either the timer or the relay. The point of saturation is dependent upon the sum of the ampere-turns available from the control and bias windings.

The bias resistors are set so that as V_2 deviates beyond some predetermined value above the reference voltage, sufficient control current flows to saturate the "lower" magnetic amplifier, thus starting the "lower" timer.

The timer will run as long as this over voltage exists. When some accumulated time period builds up to the pre-set value, the timer actuates the auxiliary relay. This time delay prevents the occurrence of unnecessary tap changes due to short-time transient voltages. The tap-changing mechanism then acts to lower the transformer voltage in 5/8 per cent increments. Provision is made to reset the timer during the tap change. A similar sequence of events takes place for an occurrence of under voltage at the load. The voltage level (V_2, Fig. 2b) often used is approximately 120 volts. A band width setting of ± 1 volt refers to a ± 1-volt variation allowable in V_2 before the timer will run. The band width of 2, 4, or 6 volts can be chosen by the customer. Tap changes always occur so as to move the operating voltage level to within the specified band width. The customer may choose to have the relay initiate tap changes continuously

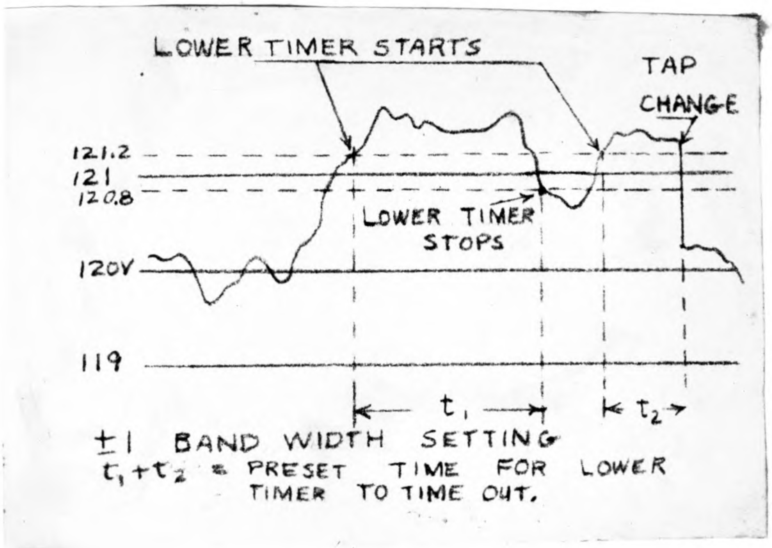


Fig. 3.

until completely within the bounds of the band width setting, or he may connect the relay circuit so as to actuate only one 5/8 per cent tap change when the timer times out, regardless of the existing voltage level at that time.

The magnetic amplifier, as will be later explained in more detail, can be made to saturate at 0.2 volt beyond the band width, and trip off at 0.2 volt inside the limit. This gives a 0.4-volt deviation range for on-off control of the timers. This range can be easily increased by means of adjustment of feedback resistance (explained later).

The setting of bias resistors determines the point of tripping for the magnetic amplifier and these resistors must be preset to agree with the corresponding settings on the band width switch.

The Sola of Fig. 1 is a constant voltage transformer which serves to hold the reference circuit at constant voltage for comparison with the load voltage V_2.

Problems with the Original Circuit. Several studies were made toward improving the operation of the original control circuit. For example, the accuracy of representation of the IZ drop in the line drop compensator is somewhat affected by whatever control current flows through this LDC. Not only does the control current magnitude affect this accuracy, but also the wave shape of this current should be given some consideration.

Better tripping was another goal of this study. In other words, it is desirable to get a positive on-off switching characteristic on only a small load voltage deviation. If possible, the timer voltage should also drop to below 10 volts when the magnetic amplifier trips off.

Another problem concerns the aging properties of the rectifiers in the magnetic amplifier output. This is important since a changing back resistance of these rectifiers would change the feedback characteristics of the magnetic amplifier at some future date.

Record of Progress

The Filter Circuit. (Refer to TE8778B, Fig. 36.) The input current to the rectifier of the sensing circuit was first measured and pictured on the oscilloscope, as shown in Fig. 38c. This current was measured with the magnetic amplifier control winding current balanced to zero. Balancing the circuit to zero was originally accomplished by setting the variac (T_1) to 120 volts and tapping down on R_3 until the milliammeter (amp to common) reads zero. The capacitor input filter takes an input current which is sharply spiked. Even though the current in lead 21 has an rms value of only 33 ma, the spiked appearance of the wave shape indicates harmonics which would have a pronounced effect upon the LDC circuit. The peak value of the spike was 114 ma.

A picture was observed of the filtered voltage (from point 31 to 23) and the a-c ripple was 3.2 volts peak-to-peak while the average volts measured 165 volts. This ripple is relatively small, but it might be observed at this point that the difference in sensing voltage and reference voltage is the important thing in this control circuit. The magnetic amplifiers are set to trip on and off with about 0.4-volt variation in 120 volts. Therefore it is desirable that the output ripple of both sensing and reference voltages be in phase to some degree. Actually this problem is of little significance here as the circuit has a fairly large time constant. Also both the sensing and reference filtering circuits are built alike.

In order to reduce filter current and reduce its spike as well, C_1 and C_3 were removed and L_1 and L_2 were replaced with 9-henry values (originally 1.5 henry each). (Refer to Experiment No. 1, Appendix.) By use of this choke input filter the rms current (I_2) was reduced from 33 ma to 22.5 ma, the Sola current (I_3) was reduced from 128 ma to 112 ma, and the input current to

T_1 reduced from 145 to 132 ma. In addition to this reduction in current magnitudes, the spike of 114 ma in I_2 which was present has been virtually eliminated.

Next it was necessary to investigate the effect of the lower voltage outputs of the choke input filters. It was noted that with 120 volts at T_1 secondary, the d-c output of the reference had dropped to 109 volts direct current, while that of the sensing circuit was 104 volts. This was as expected. The rms output of these filters should be in the neighborhood of 0.9 times the rms input (from the full-wave rectifier). The reason for the reference voltage being higher than the sensing voltage is due to the higher output of the constant voltage Sola. The Sola is known to give very good regulation (within ±1 per cent) for a given load. However, when operating at reduced load (as in this study), the Sola gives a distorted output voltage wave and may show an output voltage of considerably above rated value. This was the case here. The rating on the Sola T_2 was 118 volts at 15 va. The load condition was less than 3 va.

Adjusting the potential divider at R_3 was not sufficient to bring the magnetic amplifier control winding current to zero. The output voltage of the variac (T_1) was temporarily raised to 126 volts, thereby allowing adjustment of R_3 for the purpose of balancing I_4 to zero.

As an alternative method of balancing I_4, the bleeder resistance (R_6) in the reference circuit was tapped down some 1800 ohms in 12,500. This reduced the reference voltage to about 93 volts and in this way R_3 could again be used for adjustment from the center of its range.

The Sola Circuit. The next change in the circuit was in moving the Sola input from point 18 to point 3. The purpose for this was to further reduce the control current passing through the LDC. The disadvantage of this move is that the Sola input was then taken from the main transformer secondary voltage (V_1) rather than the regulated load voltage (V_2). This input voltage variation could then alter the reference circuit direct-current output. A test was made on the 115-volt Sola to determine its regulation. (See Appendix, Experiment No. 2.) In order to get an accurate measurement of the direct-current output variation for the reference circuit, this direct-current output was placed in opposition with a constant value of voltage and their difference was measured on a low-scale direct-current voltmeter. Curves of Fig. 40 apply here. Here it is seen that the curve of $V_{x\ d\text{-}c}$ versus V_{in} of the Sola flattens out on either side of the 105-volt input. Between 120 and 140 volts input there is only a 0.2-volt variation in direct-current reference volts. Better results yet were obtained by using a step-down autotransformer, shifting the input to the Sola by the ratio of 120 to 105. The II-B curve of Fig. 40 shows the effect of the added autotransformer. V_x on the curves was an arbitrary voltage difference between the reference output voltage and some other arbitrary voltage held constant. Only the variation in V_x is significant. It was hardly practical, nor does it seem necessary to provide this added autotransformer for improving Sola regulation.

Having evidence that the Sola lead can be moved to point 3 without altering the reference appreciably, this new test was made with the results shown in Experiment No. 1, Part III a, Appendix. The current I_1 which flows through the LDC was further reduced to 80 ma. This change alone reduces this current by about 40 per cent. To get an idea of the control current which can be tolerated through the LDC, it should be remembered that under rated load conditions, 5 amperes flow through the variable R and X of the LDC. The potential transformers CPT_1 and CPT_2 are approximately 1:5 ratio, the higher voltage being on the control circuit side. This means any current which flows into point 16 is reflected into the LDC 5-ampere circuit with five times its magnitude. For example, the 145-ma control current which existed originally would be reflected into the line drop compensator circuit as 0.725 ampere, which is 14.5 per cent of the magnitude of the 5 amperes which represents the customer's rated load. With 80 ma flowing into point 16, the effect is reduced considerably.

<u>The T_1 Variac</u>. One other significant improvement was made in the further reduction of control current through the line drop compensator. This change involved the replacement of the variac T_1 of Fig. 36. This variac was found to be drawing 63 ma of exciting current at 120 volts input. This variac was replaced with an autotransformer in conjunction with a variac, as shown in Fig. 4. The autotransformer was one of low exciting current. Also the connection shows that the variac has only 40 volts applied, meaning that its exciting current will be small as well. If the load is removed it may easily be shown that

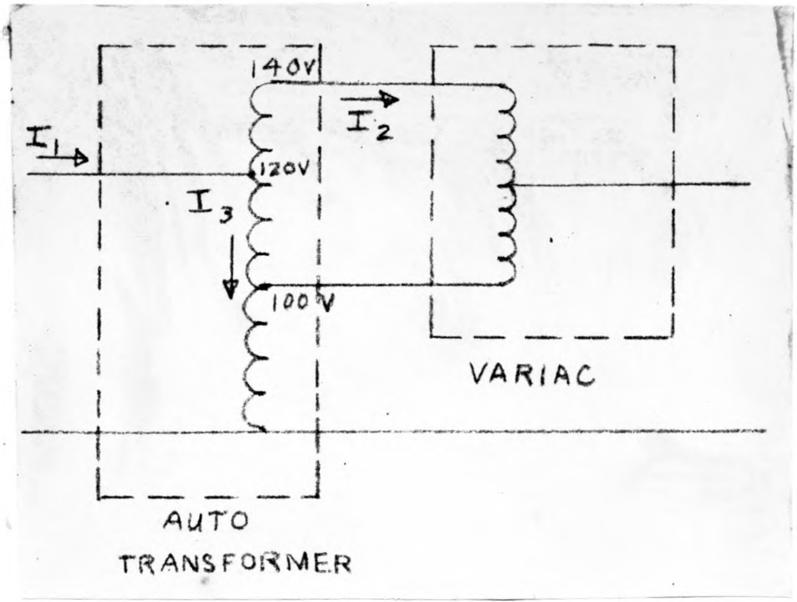


Fig. 4.

$I_1 = I_{ex_1} + 0.333\ I_{ex_2}$, where I_{ex_1} is the current normally required to excite the autotransformer core and I_{ex_2} is that required to excite the variac core. Both I_{ex_1} and I_{ex_2} are small, as explained earlier. Actual exciting current when measured (of the combination) proved to be 10.9 ma, only 17.3 per cent of the excitation required for the original variac. One other advantage gained by this change is in a finer voltage control for the sensing circuit. Later it will be shown where this finer control may be used to good advantage in the elimination of the "amp adjust" potentiometer.

To summarize the progress up to this point, the following changes were made and the circuit tested, as shown in Fig. 41.

1. Change from capacitance input to choke input filters on both reference and sensing circuits.

2. Bleeder resistor of reference tapped down.

3. T_1 variac replaced with autotransformer and variac.

4. Sola input moved from point 18 to point 3.

At this point it was found that the bias resistors were too small in the ±3-volt band width. Less bias current was needed for the simple reason that the available control current has been reduced for any given band width. The control winding current was reduced because the d-c voltage level for both references and sensing circuits has been reduced by the ratio of about 104/165, as explained previously.

At this time no mention will be made of the values of these bias resistors, as there are several other circuit changes which will again affect the values of bias. In order to balance the magnetic amplifier circuits, temporary bias resistors were used at this point.

Once again, the reduction of control current through the LDC will be mentioned. In going from 145 to 21 ma, the effect of this current upon the LDC has been reduced to 14.5 per cent of the original value, or from a reflected value of 0.725 ampere (0.145 x 5) to 0.105 ampere (0.021 x 5). The value of 0.105 ampere represents only about 2 per cent of the 5 amperes in the LDC circuit which represents the rated load current. This should be permissible.

Magnetic Amplifier Feedback. Silicon diodes are known to have better aging properties than the selenium rectifiers which were in use in the "original" circuit at the point of magnetic amplifier output. In other words, the back resistance of the silicon diode does not change appreciably with age. At this point it is necessary to discuss briefly the principle of operation of the magnetic amplifiers in use.

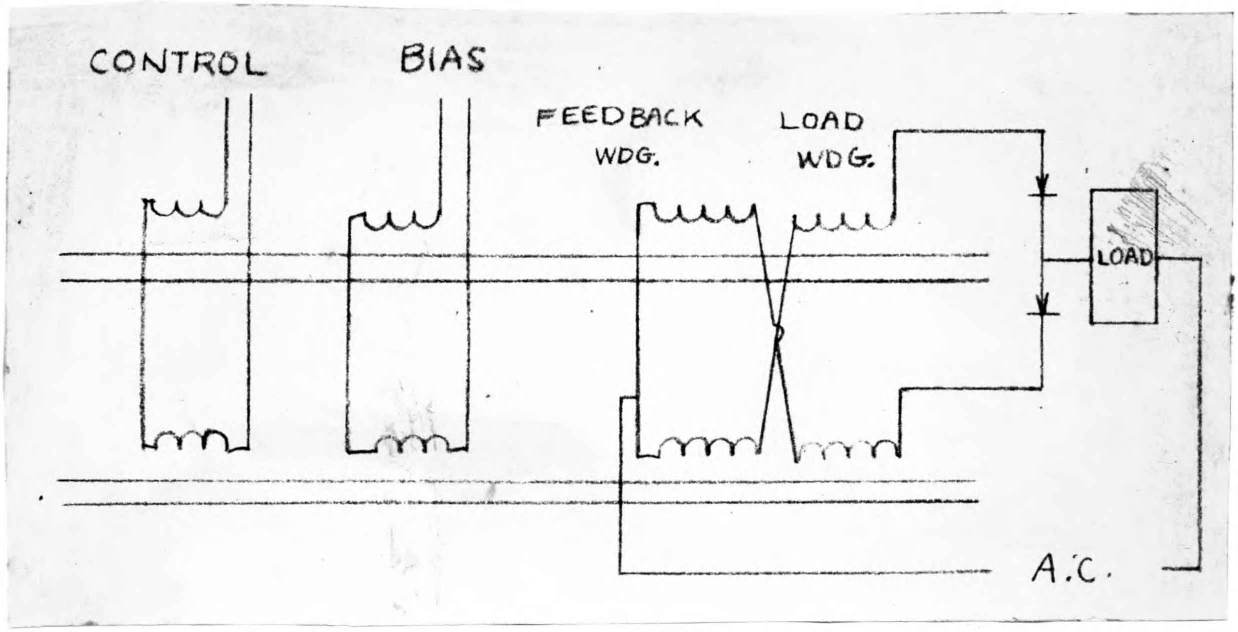


Fig. 5.

Each of the magnetic amplifiers includes two separate cores. The diodes shown in Fig. 5 allow current to flow in one direction only through the load windings. Ordinarily the inductance of an iron-cored coil is proportional to the slope of the B-H curve. ($B \propto \phi$; $H \propto I$, $L \propto \frac{d\phi}{dI}$.) The function of the magnetic amplifier here is to effectively place a high or low impedance in series with the load, which has the effect of a switch in either on or off position. The magnetic amplifier without feedback has a steep linear slope with fairly definite saturation points. Since it is necessary to have a bi-stable condition where there is no intermediate point between on and off, positive feedback is used. Saturation is dependent upon total ampere-turns present in the bias, control, and load windings. Positive feedback is obtained by adding an extra winding to each core, as shown in Fig. 5. The feedback winding of one core, for example, is placed in series with the load winding of the other core. Load current flowing through the feedback winding will set additional flux in the core, which gives a negative slope to the curve of I_{load} versus $I_{control}$, as shown in Fig. 6. The method of controlling feedback in this circuit is by means of assigning proper values to R13 and R14 which appear across the load rectifiers. These resistors provide a path for allowing a back current

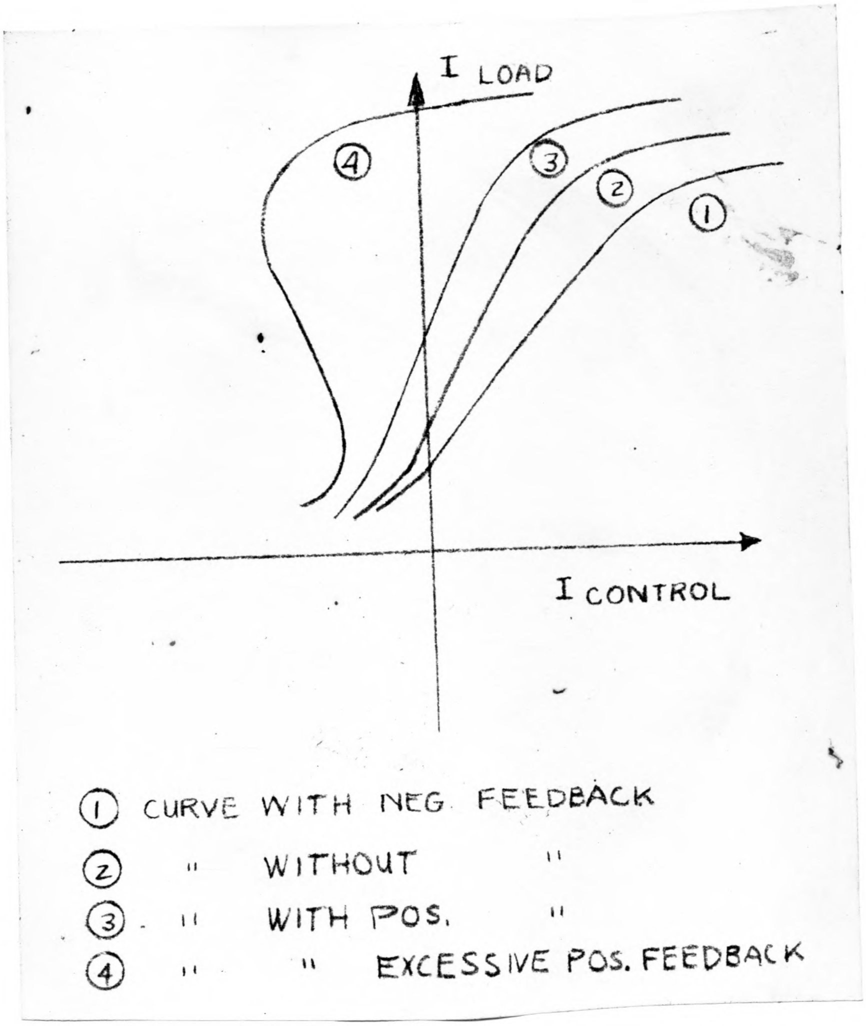


Fig. 6.

to flow during the normal nonconducting half cycle of the load winding. This back current has the opposite effect upon feedback that the forward current has, since it serves to nullify part of the positive feedback ampere-turns. It can be seen from this that if selenium rectifiers were to be used, any reduction of back resistance with age will change the slope of the load current curves in Fig. 6. Aging properties are important since the unit is built to operate for 20 to 30 years.

Increasing the positive feedback by increasing the back resistance will normally give a more positive switching action. However, this is done at the expense of requiring more deviation control current between the "on" and "off" switching points. (See Fig. 7.) Adjusting the bias resistors merely shifts the load-current curve to the right or left, but does not change its shape.

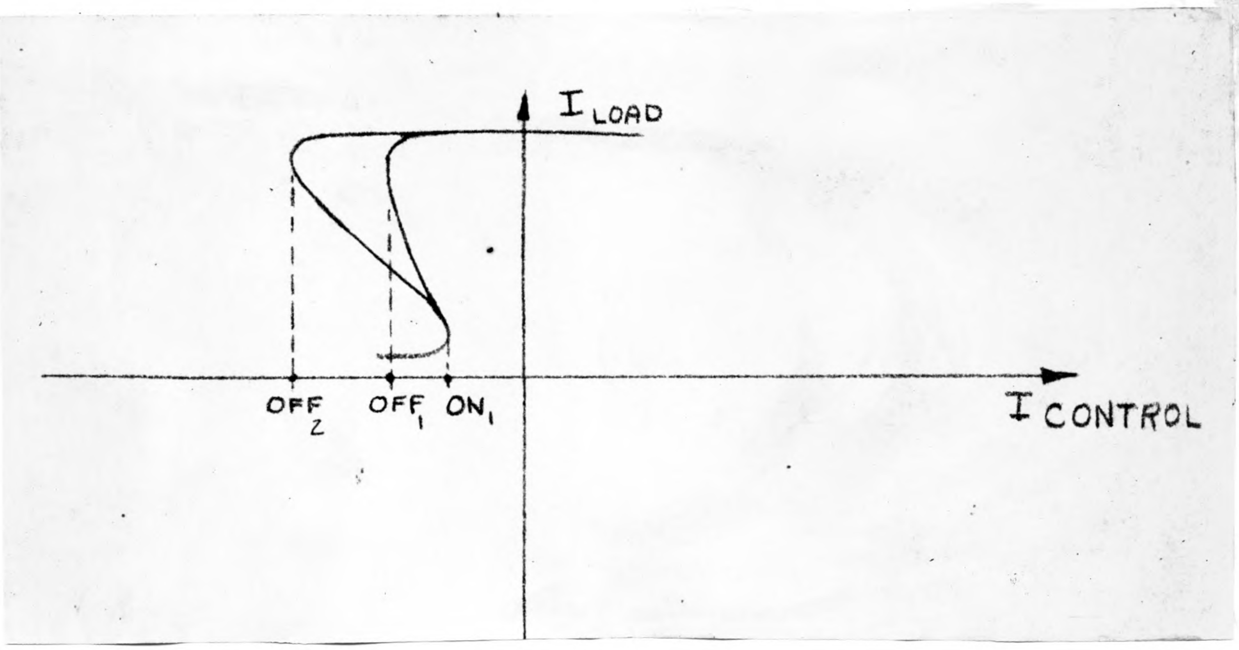


Fig. 7.

The Magnetic Amplifier Load Circuit. A test was next made on the lower timer circuit to determine whether proper operation of the load circuit was possible using the changes in the circuit up to this point. The main objects of concern here are band width, positive switching action, and voltage deviation necessary to go from the "on" to "off" condition. It should be possible to set all three of these characteristics by means of two simple adjustments: bias resistors and feedback resistor. However, it was found that even though a fair snap action was obtainable within proper limits of a-c voltage deviation, the off voltage existing across the timer (at the time of switching) was from 10 to 15 volts. This was often sufficient to keep the timer running.

The method for testing the action of the control circuit was by means of a test set built by the Wagner service department. A voltage of 120 volts was applied to the input of variac T_1, with the fuse at lead 16 removed. The test set, in this way, was used only for supplying the voltage to the sensing circuit, representing the customer's load voltage (V_2). At the same time, removing the fuse made it possible to supply the reference circuit and timing circuit from a source other than the test set. The reason for this is, obviously, that any additional loading of the test set might alter the value of V_2 appreciably. This is especially true in the event of tripping of the magnetic amplifier when the timer circuit draws extra current. The circuit was balanced as described earlier and the change in V_2 necessary to unbalance the circuit to the point of tripping was then recorded. This voltage was accurately measured by means of a deviation voltmeter provided with the test set. See Fig. 8 for a view of the expanded scale which was accurate to about 0.05 volt. This deviation meter is most convenient in checking the "on-off" switching for the three band widths.

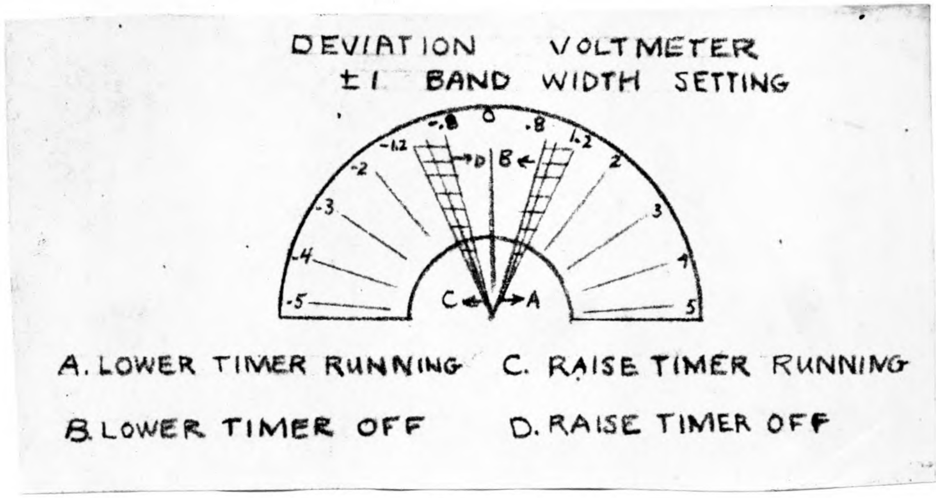


Fig. 8.

In order to be sure that the timers would stop at the end of switching, a 3500-ohm resistance was placed in series with the timer. This value of resistance was used as a result of calculations connected with Fig. 48. This shows the timer impedance to be about 3000 + j2000 ohms. This series resistance reduced the timer current from 32 to 15 ma. This reduction of magnetic amplifier load current at the same time changed the effect of positive feedback since feedback is dependent upon load current. This brings up the need for having a timer impedance which somewhat matches the relay impedance. Relay current was found to be 52 ma, which means more control deviation volts necessary to open the relay than is necessary to shut off the timer, as shown in Fig. 9.

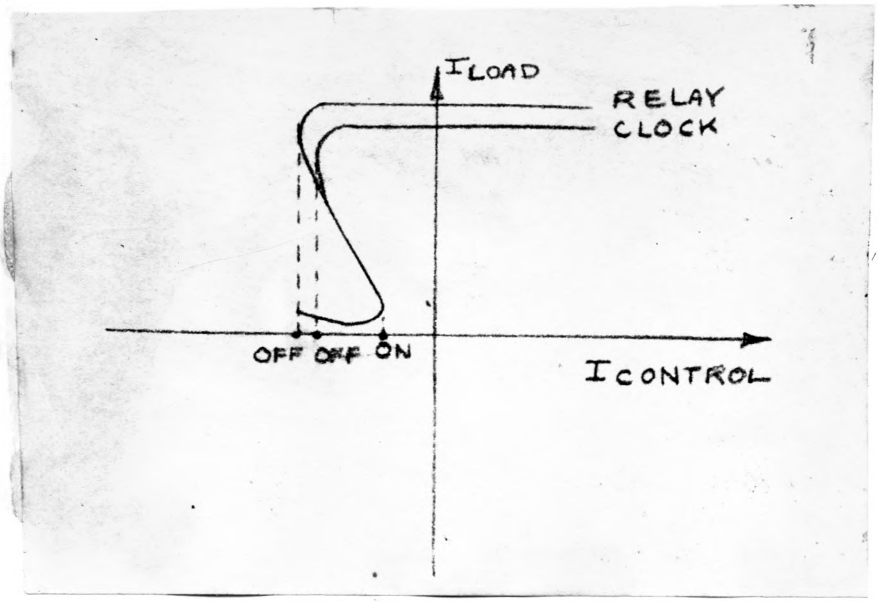


Fig. 9.

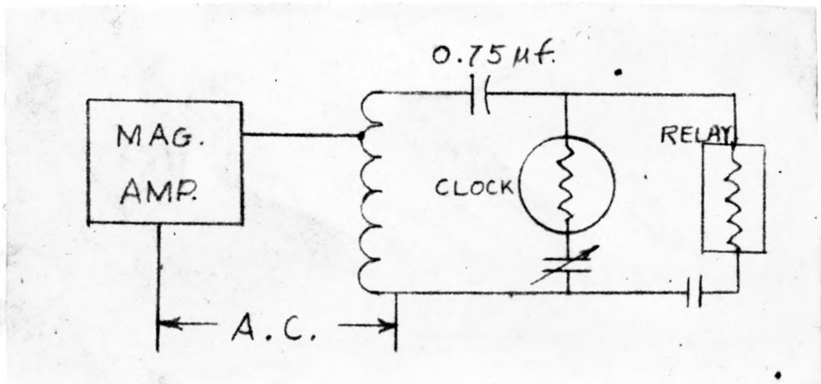


Fig. 10.

Figure 10 shows the original load circuit which used the series capacitance to raise the load voltage and as a means of power factor correction. The magnetic amplifier resistance was on the order of 500 ohms at saturation and its inductance varies, of course, upon the degree of saturation of its core. This impedance of the magnetic amplifier drops considerable voltage even when in the saturated condition. This necessitates the use of the autotransformer (T_6).

In order to equalize the loading of the magnetic amplifier for both timer and relay circuits, these circuits were converted to their equivalent parallel values. Then they were matched by the addition of capacitance in parallel with the relay and resistance in parallel with the timer. This matching did guarantee that both timer and relay circuits tripped alike. The problem of fairly low timer voltage at running and some tendency for the relay to hunt when in the process of switching off still remained. As a result this line of approach was abandoned.

Improving Magnetic Amplifier Sensitivity. It was reasoned that much of the problem encountered in magnetic amplifier switching could be eliminated by improving the sensitivity of the control winding circuit. The sensitivity had been reduced considerably while making the change to choke input filters. Several reasons can be given for this: (1) Additional choke resistance, (2) reducing the d-c voltage level of both filter outputs, (3) tapping down on the bleeder resistance of the reference circuit.

In order to improve the sensitivity of the control circuit, the reference and sensing network was reduced to Thevenin's equivalent circuit. Figure 44 and Table 2 apply here. Each control winding was found to contain approximately 480 ohms resistance. The 9-henry choke contained 500 ohms resistance. Sensitivity was improved by connecting two control windings in series for each magnetic amplifier. Sensitivity was also improved by eliminating the tap-down resistor R_3 and tapping down only about 420 ohms on the bleeder in the reference circuit. Total increase in sensitivity with these three changes was improved to over 300 per cent of that obtained immediately after going to the choke input filter.

In eliminating the tap-down resistor R_3, the potential divider marked "amp adjust" on the control box was eliminated. The function of this 2500-ohm potentiometer may be accomplished as well with the variac (T_1). As previously explained, the new autotransformer and variac combination (which replaced the original T_1 variac) allows finer voltage adjustment than was possible in the original circuit. The panel voltmeter was connected across the output of T_1, and for balancing the control current to zero this voltage was first set to 120 (in the original circuit) and next the "amp-adjust" potentiometer was used to further balance to zero. Now without the use of the "amp adjust", the variac voltmeter may not read exactly 120 volts upon balancing. In reality this voltage is an internal voltage and has no real significance. It might even be better to do away with this reading as it does not necessarily represent either the customer's load nor does it represent the main transformer voltage. For example, if the tap-down resistor of the reference circuit were eliminated altogether, this voltage might read on the order of 126 volts when the circuit is balanced. This should not disturb anyone once it is understood that this voltage is not significant. At the same time it should be mentioned here that eliminating this tap-down resistor of the reference circuit would actually improve the sensitivity another 20 to 30 per cent. Should it be desired (at some future time) to further increase sensitivity, the chokes being used in the filter circuits might be replaced with values of the same inductance but lower resistance. Table 2 shows the advantage of this move.

Correcting the Bias. The ohmic values of bias resistors (slide-wire) needed at this point did not compare too well with those used in the original circuit, since the control winding current was higher for a given deviation voltage. This means, of course, that for a given band width, the bias current must be increased.

In increasing the bias current, a new problem was presented. Positive switching could be obtained for the ±1-volt band width but very sloppy switching was observed for the ±3-volt band width (same feedback resistance value). It was reasoned that this was due to the nature of the bias current which was a pulsating unfiltered direct current. Higher values of this pulsating current meant that a larger a-c component was present in the bias winding. This a-c component had the effect of nullifying a part of the positive feedback available from the pulsating load current winding. In order for the bias winding to work better with the control winding current (which was well filtered), a 1.5-henry choke was placed in series with the bias resistors. This proved sufficient for smoothing out the bias current, as was observed on the oscilloscope. The choke did offer enough impedance that the 117/6.3-volt bias transformer was replaced with one having a 117/12.6-volt rating. A new test verified the theory of the adverse effect of the pulsating bias upon feedback, and with the 1.5-henry choke all band widths worked well from the same setting of feedback resistance. Good operation was then obtained with the following approximate values of bias resistance: ±3 band - 150 ohms; ±2 band - 275 ohms; ±1 band - 480 ohms. (Refer to

Experiment No. 4, part IIb, Appendix.)

Trimming the Magnetic Amplifier Load Circuit. After improving the sensitivity of the load circuit, attention was then shifted back to the load circuit of the magnetic amplifier. The objects of this study were to reduce the "off" voltage of the timer while maintaining a sufficient "on" voltage and to eliminate any tendency for "hunting" of the relay in opening. Again starting with the original load circuit in Fig. 10, the 0.75-mf capacitance was removed altogether. The clock and relay worked fairly well together, with the timer "off" voltage dropping well below the value needed to stop the timer. However, the relay voltage was only 85 volts on a coil rated for 115 volts. A 90-volt coil did not prove satisfactory. For one thing the 90-volt coil draws excessive current as compared with the 115-volt coil. This makes a poor match when considering the timer and relay circuit together.

The next consideration was comparing the method of power factor correction in the original circuit with that of placing a capacitance in parallel with timer and relay. (See calculations for Experiment No. 6, Appendix.) Here again, all values of impedances in the magnetic amplifier load circuit were approximated and referred to the low-voltage side of the autotransformer (T_6). Even the mutual impedance of the autotransformer excitation branch was approximated. It was then determined what value of parallel capacitance would throw the relay circuit into resonance. This calculated about 1.2 mf and gave minimum current through the magnetic amplifier of about 90 ma. Any further increase in capacitance would cause relay voltage and magnetic amplifier current to go up together. A value of 1.5 mf brought relay voltage to 105 volts and at the same time corrected the tendency for "hunting" that was present in the series capacitance method of correction. It is difficult to show (by calculation) the reason for this quicker opening of the relay because each change in load current changes the impedance of the magnetic amplifier. However, a qualitative explanation can be given for this. In the original method (Fig. 11a), Z_m = magnetic amplifier impedance and Z_t = transformer mutual impedance, where Z_R and X_c are both referred to the L.V. side or left of a-b. When the relay attempts to open, its air gap increases and X_R goes down. At the same time $X_c > X_R$, which makes the circuit to the right of a-b capacitive. Since Z_m is inductive, V_{ab} tends to rise suddenly as does the current I_m. A higher I_m tries to shift the magnetic amplifier to a new curve requiring less control current for switching off, as shown in Fig. 11b. The relay again closes and the hunting cycle repeats due to increased I_m and increased V_{ab}.

The following reasoning holds when using the parallel capacitance of Fig. 12. As the relay attempts to open, X_R decreases and the load circuit to the right of ab becomes inductive, while I_m and V_{ab} decrease, both of which will aid in the opening of the relay. Thus "hunting" is eliminated.

One additional scheme proposed to assure an even more definite stopping of the timer (at 20 to 30 volts) is to add drag to the timer rotor by means of a small permanent magnet attached to the periphery of the timer. This is yet to be tested.

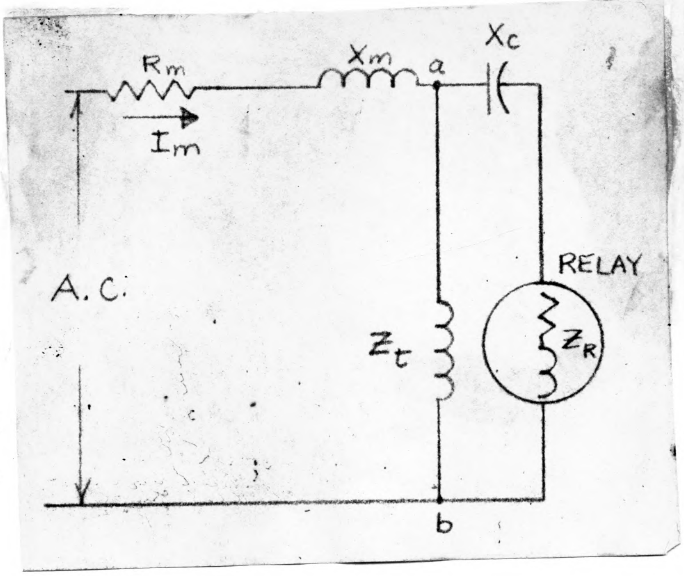


Fig. 11a.

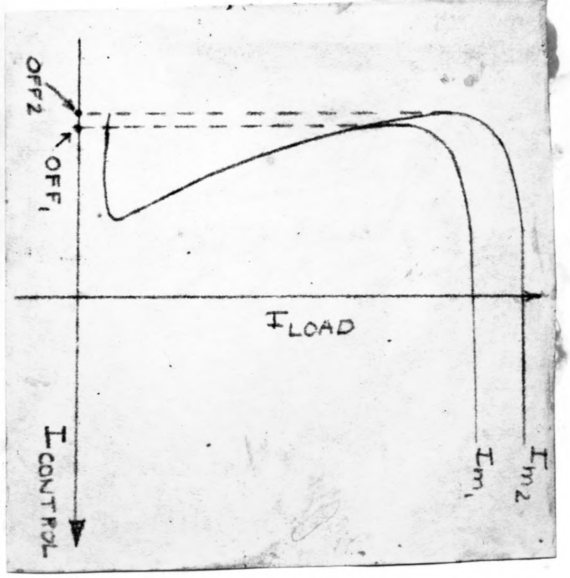


Fig. 11b.

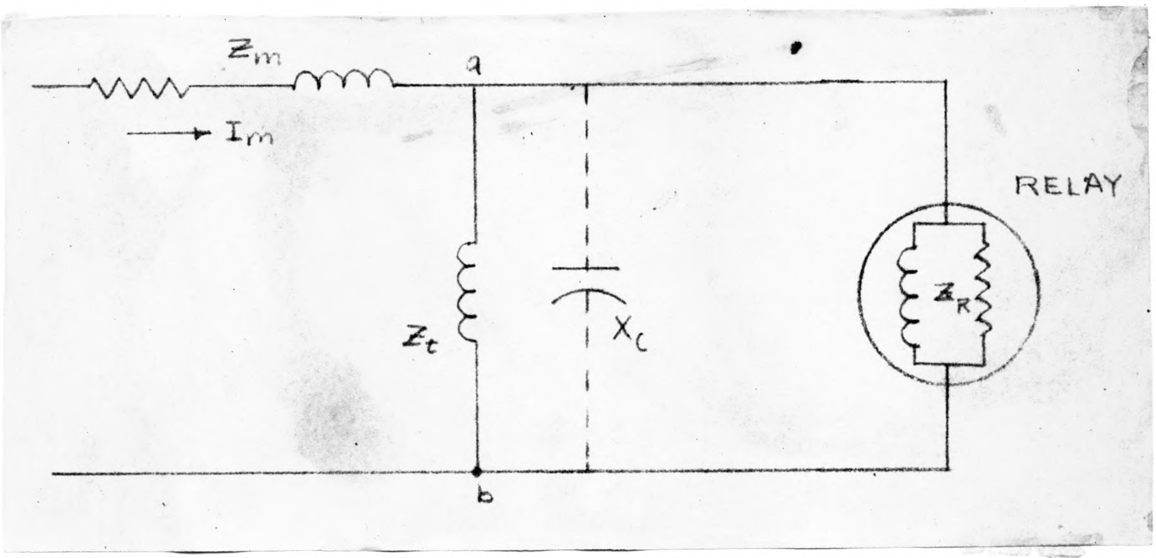


Fig. 12.

Summary of Control Circuit Changes

The following improvements have been made on the "original" LTC control circuit.

1. Control current through the line drop compensator

was reduced from 145 ma to 21 ma.

2. More definite snap action of the magnetic amplifier was made possible for a given variation in customer load voltage, due to improved sensitivity of the control windings.

3. Tendency of relay to "hunt" while in the process of opening was virtually eliminated.

4. Timer voltage drops further when the magnetic amplifier switches "off". This gives assurance that the timers will stop at the bottom of switching without requiring additional control to stop them.

5. Problem of aging of the magnetic amplifier rectifiers is corrected.

The following is a listing of changes made in the components of the "original circuit.

1. Eliminate C_1 and C_3.

2. Replace L_1 and L_2 (1.5 henry) with 9-henry chokes. (Resistance of choke greatly affects sensitivity, as mentioned in body of report.)

3. Move Sola input lead from lead 18 to point 3.

4. Replace the T_1 variac with autotransformer and variac combination.

5. Eliminate the "amp-adjust" potentiometer. Retain R_4 and R_5 as bleeder resistor of sensing circuit.

6. Place the extra control winding of each magnetic amplifier in series with winding already in use.

7. Tap down about 420 ohms on the reference circuit with a slide-wire resistor--due to high reference voltage.

NOTE: Better sensitivity obtained if needed by eliminating this tap-down resistor even as R_3 was eliminated. Variac T_1 will read higher voltage, of course.

8. Add 1.5-henry choke in lead 36 of the bias circuit.

9. Change the bias transformer (T_5) from 117/6.3- to 117/12.6-volt rating.

10. Exchange the selenium rectifiers of the magnetic amplifier output with silicon diodes.

11. Eliminate C_5 and C_6.

12. Place 1.5 mf in parallel with the magnetic amplifier load circuits (across points 51-17 and 58-17.

13. Test the merits of adding rotor drag to timer using an attached permanent magnet. The purpose of this is for assuring stoppage of the timer at a higher value of magnetic amplifier "off" voltage.

PART II. THE LINE DROP COMPENSATOR

The purpose of the line drop compensator (LDC), as explained in Part I of this report, is to simulate the line voltage drop which is present between the main transformer secondary terminals and the customer load circuit. After having reduced the magnitude of control current which passed through the LDC, the next step was to determine other sources of error which might be present in simulating the IZ drop of the line. A schematic diagram of the line drop compensator is shown in Fig. 13. The current transformer shown in Fig. 13 steps down the customer's line

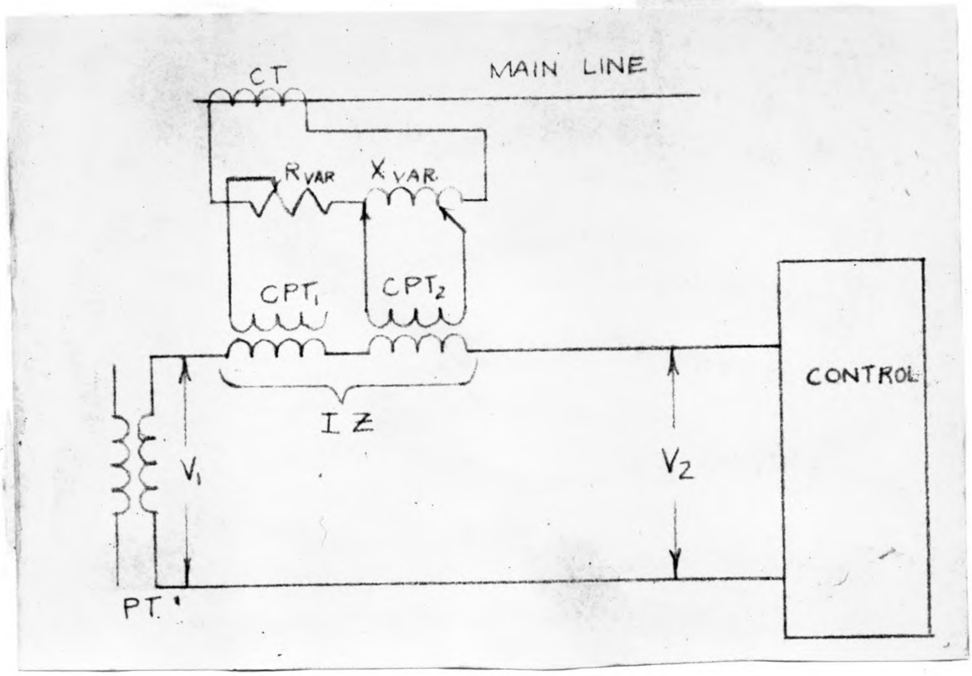


Fig. 13.

current to a 5-ampere base and sends this representative load current through a variable R and X. These variable components represent the impedance of the line. It is not feasible to feed the actual customer load voltage (V_2) into the tap changer control circuit when the load and transformer (with tap changer) may be located many miles apart. The customer should see a true representation of the load voltage (V_2) with the proper values of R and X set on the dials. Refer to control panel photograph of Fig. 35. The value of V_1 is taken from a potential transformer at the main transformer secondary terminals. This potential transformer has a 120-volt secondary winding, since this is the base voltage of the control circuit. If the LDC is accurate, then $\overline{V}_1 = \overline{V}_2 + \overline{I}\ \overline{Z}$. The $\overline{IZ}$ drop is taken from CPT_1 and CPT_2. These are potential transformers used to step the voltage up from 5 volts to 24 volts. This value of 24 volts is obtained with all of R or X in the circuit and with rated current in the line. R_{var} and X_{var} are about one ohm (maximum) each. The R and X dials on the front panel are each marked from 0 to 24 volts.

Errors in the LDC

A test circuit was set up to simulate the load conditions, as shown in Fig. 14. Five amperes were sent through R_{var} and

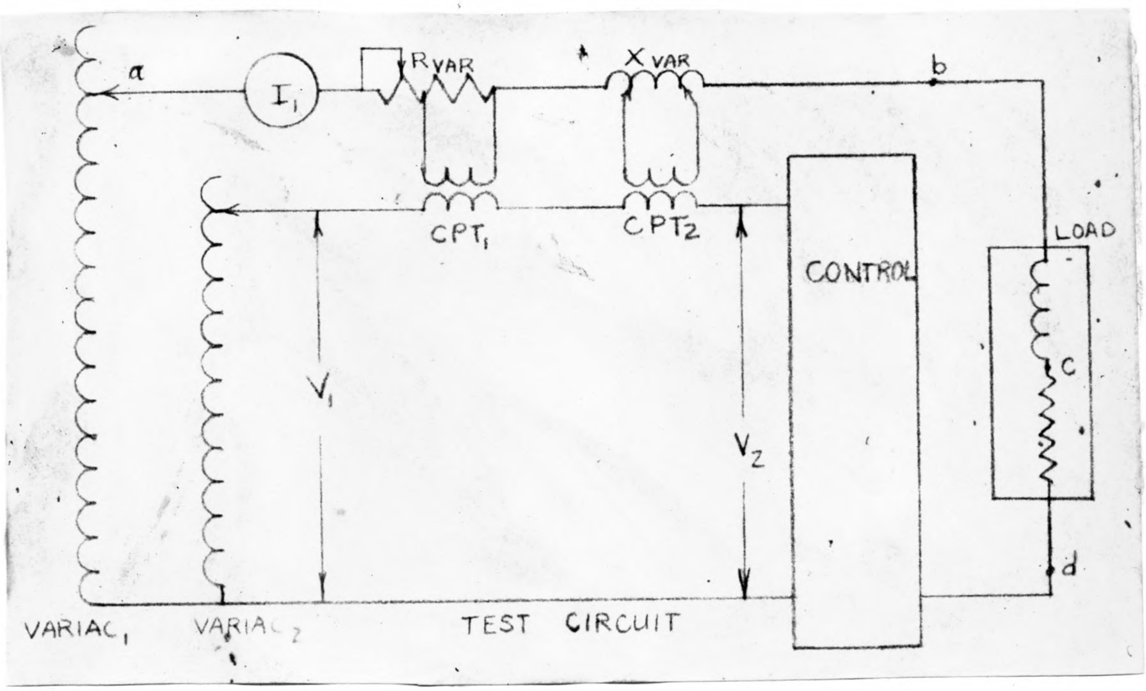


Fig. 14.

X_{var} to represent full-load conditions. To determine the power factor of this load current, three voltages were read: V_{ac}, V_{cd}, and V_{ad}. Vector diagrams then easily gave the angle of I_1 with respect to V_1. The variac No. 2 was set to give 120 volts at V_2 for a given dial setting on R and X. Then V_1 was calculated and this calculated value compared with the measured value of V_1. The equation for determining V_1 gives more accurate results than the use of vector diagrams for this purpose. The equation is:

$$V_1 = \sqrt{(V_2)^2 - (-\cos\theta \cdot IX - \sin\theta \cdot IR)^2}$$
$$- \sin\theta \cdot IX + \cos\theta \cdot IR$$

This equation is derived in Experiment No. 7, of the Appendix. V_1 was calculated two ways for each condition of line impedance and power factor. One way was to use the measured IR and IX voltages in the above equation. Another way was to substitute the actual dial settings into these equations. The angle θ in the equation refers to the angle between I_1 and V_1 which was determined by use of vector diagrams. These calculated values of V_1 were then plotted along with the measured value of V_1. See Figs. 56 and 57. The curves show the greatest deviation (in calculated and measured values) at the 24-volt settings and, for the most part, the deviations are proportional to the dial settings. The curves showing widest deviation are at the 0.8 power factor lagging current and with R and X both maximum.

Breakdown of Errors. Several reasons can be given for the deviations here. (1) Some effective resistance is inherently present in the X_{var} component, both due to copper loss and core loss. (2) Exciting currents of CPT_1 and CPT_2 affect the magnitude and phase angle of the IR and IX drops. Insofar as the IX drop is concerned, only the magnitude of this is changed appreciably by the exciting current. In the case of the IR drop, the phase angle of IR is shifted. This will be covered later in more detail. (3) The control current which flows through the secondary windings of CPT_1 and CPT_2 still has a slight effect on the IZ drops. This control current will add vectorially to the primary currents of CPT_1 and CPT_2 in such a way as to equal the exciting current required by the transformers. As will be shown later, the primary windings of CPT_1 and CPT_2 will carry a current which depends upon control current, magnitude and angle of load current, and the setting of the R and X dials.

Contribution of Individual Errors. In order to investigate the separate contribution that each error makes toward the total error, the following procedure was followed. Under various line and load conditions, V_1 was both measured and calculated, while V_2 was held constant at 120 volts. Again it will be recalled that V_1 represents the main transformer secondary voltage while V_2 represents the regulated load voltage sent to the sensing equipment. Figures 56 and 57 show a comparison of these values of V_1 found (1) by calculation using the IR and IX voltage readings behind the panel, (2) by measurement without modifications, and (3) by measurement with modifications.

Now at the three extreme conditions (at given power factor) of dial settings, a study was made of the individual sources of error. These extreme conditions are: $R = 0$, $X = 24$; $R = 24$, $X = 0$; $R = 24$, $X = 24$.

The first consideration is the simple case of $R = 24$ and $X = 0$ with a power factor of 0.996. Here the power factor was so near unity that V_2 and IR add nearly algebraically to equal V_1. No significant errors show up at this condition.

The next case ($R = 0$, $X = 24$, power factor = 0.997) contains considerable error. In other words, the measured and calculated values for V_1 differ by about 2.8 volts. Refer to calculations for Experiment No. 7 (Appendix). The reason for this deviation is due mainly to the effective resistance of the variable reactor (X_{var}). Then this R_{eff} produced an undesirable IR drop along with the IX drop. This IR drop was approximated for the 24-volt setting by adding core and copper loss as total power (P_t). Knowing the volt-amperes between point 14 and point 15, then $R_e/Z_e = P_t/V_A$. (See Fig. 15.)

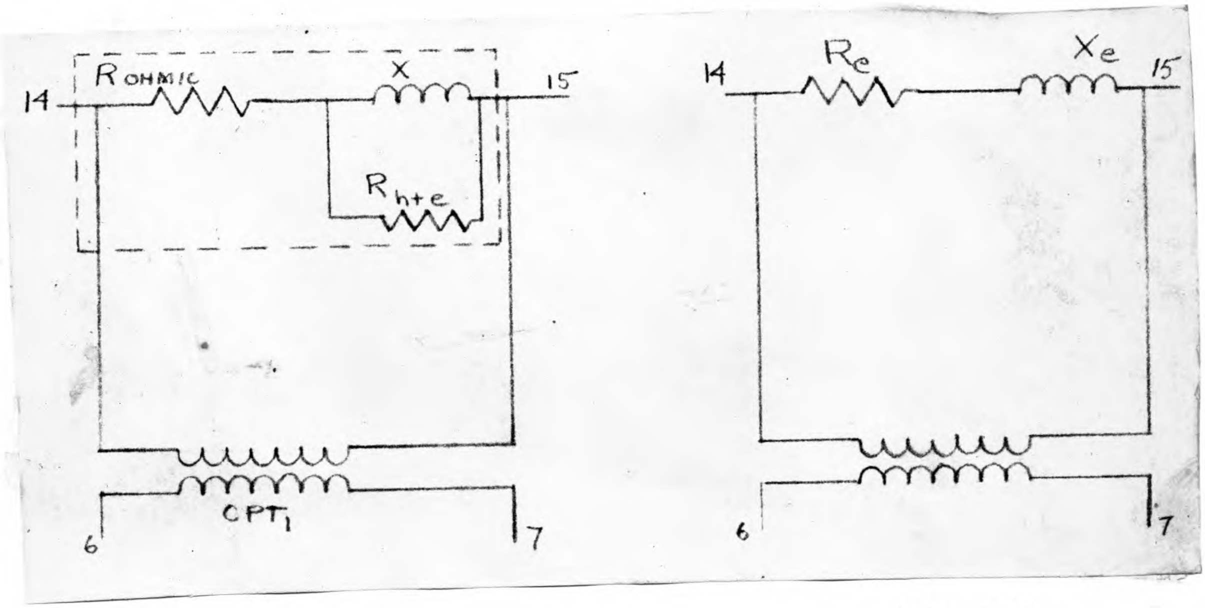


Fig. 15a. Fig. 15b.

The IR_e drop reflected between points 6 and 7 (at the 24-volt setting) is approximately 2 volts in 26.8 volts of IZ (see Fig. 15b). See Fig. 16 for a vector diagram indicating this error which accounts in the most part for the deviation voltage. The vector V_1 includes the error and compares well with the measured value of voltage. What little error is unaccounted for can be explained as resulting from control current through the CPT_1

secondary. Control current error will be considered later. It may be noted that the IX reading across points 6 and 7 measured

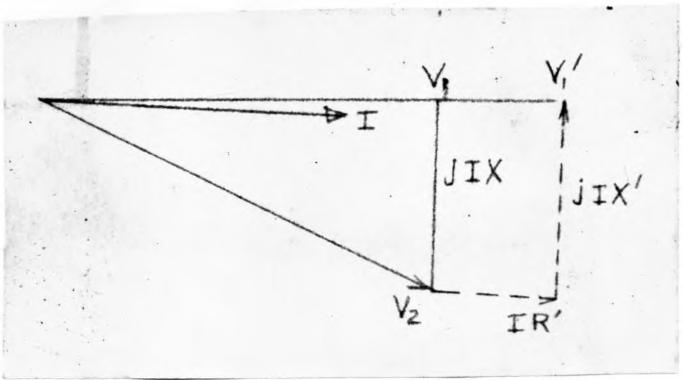


Fig. 16.

26.8 volts instead of 24 volts as shown on the dial. This offers no real problem as it is merely a matter of compensating CPT_1 for turns ratio.

The next extreme setting which is worthy of mention is where power factor = 0.809 (cosine of θ), R = 24, X = 0. This condition brings another error to light. This time V_1 measures 2.2 volts greater than it calculates. The main reason for this is found to be in the exciting current of CPT_2 as it shifts the phase angle of current through R variable. This is shown in Fig. 17. A voltage across 4 and 5 is present which is added to V_2 to give V_1. The $V_{4,5}$ is, however, a measure of $I_R R_{var} \frac{(N2)}{(N1)}$ instead of $I_1 R_{var} \frac{(N2)}{(N1)}$. Now since the phase angle of I_R is shifted 4.2 degrees from I_1, an error is introduced in V_1. (Refer to Fig. 18.) The calculated V_1 expected when considering this error closely corresponds to the actual measured value of V_1.

An example of a condition when all errors are present and

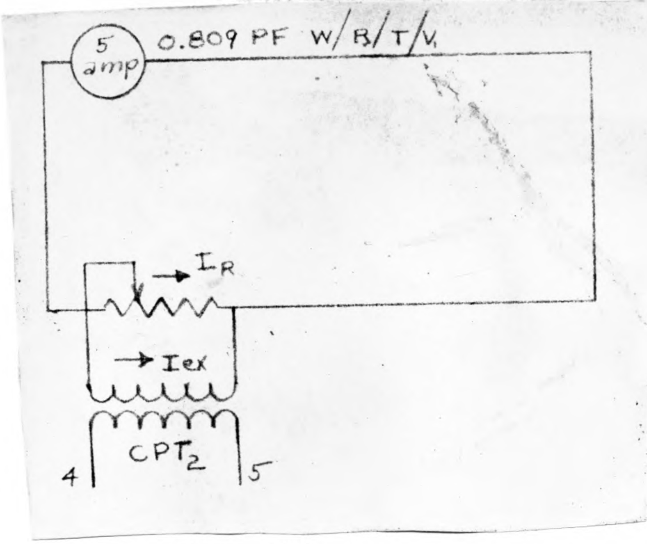


Fig. 17a.

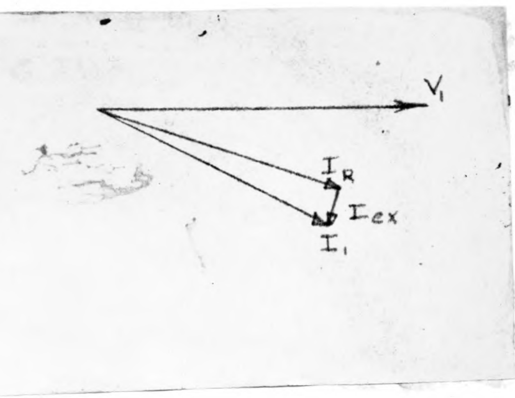


Fig. 17b.

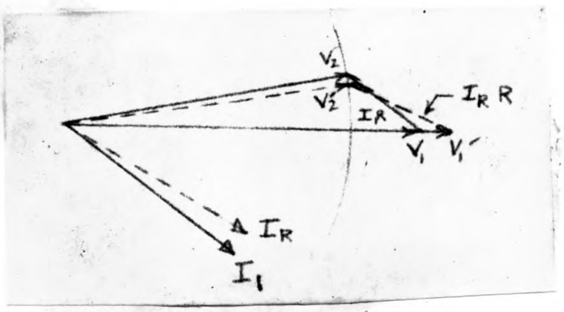


Fig. 18.

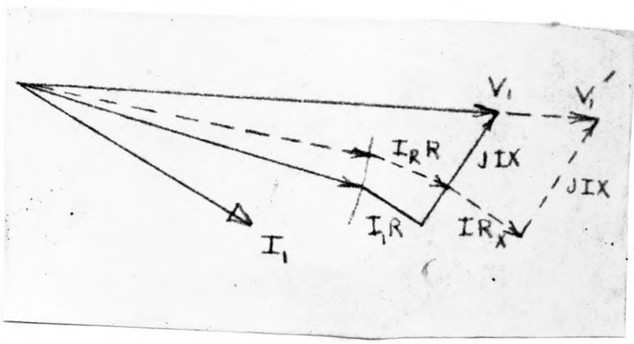


Fig. 19.

appreciable is the condition of 0.814 power factor, R = 24 and X = 24. There the voltage V_1 is 6.5 volts different in calculated and measured values. Figure 19 shows the effects of all errors in the circuit. The dotted lines represent the position of vectors with errors included. This is merely a quantitative vector diagram. The resistance in X_{var} increases V_1 and the phase shift of I_R which rotates the $I_R R$ vector counterclockwise to increase V_1 even further.

Now some attention will be given to the effect of control current upon the IZ drop of the compensator. First, considering the potential transformer CPT_2, about 0.021 ampere (I_C) flows into the control circuit. When based on the primary of CPT_2, this is about 5 x 0.021 = 0.105 ampere. This current added vectorially to I_2, as shown in Fig. 20c, must equal the excitation current required to excite the secondary at 24 volts. This excitation current equals about 0.35 ampere at 24 volts. The control current, though not sinusoidal, lags V_2 by about 45 degrees. This was pictured on the oscilloscope in order to arrive at the approximate vector diagrams of Figs. 20b and 20c. This is a

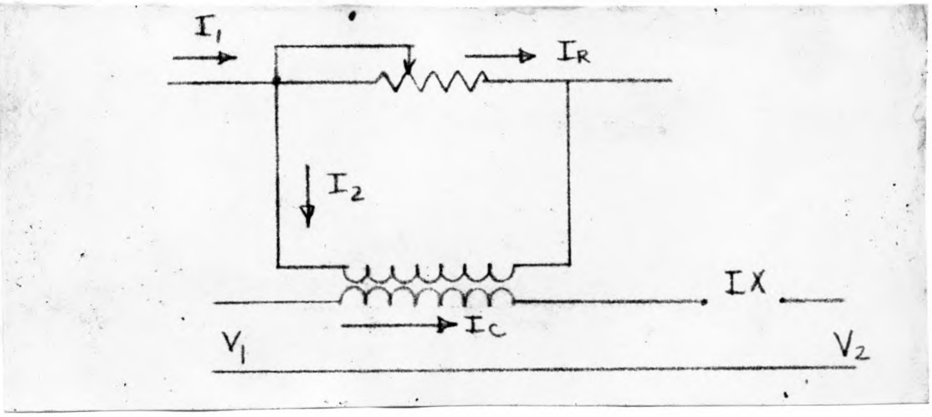
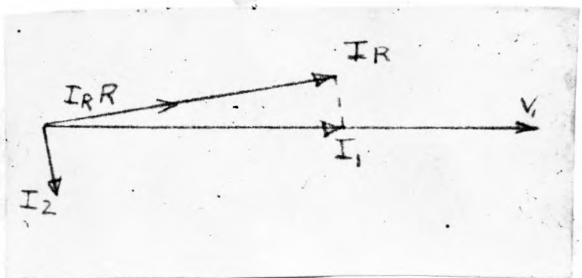


Fig. 20a.



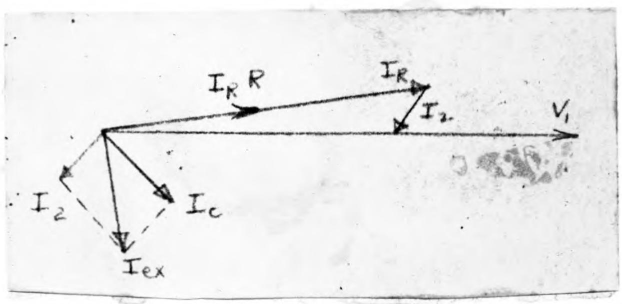


Fig. 20b. (Without I_c). Fig. 20c. (With I_c).

condition of unity power factor of the main transformer. In Fig. 20b, $I_1 = I_R + I_{ex}$, since without control current, $I_2 = I_{ex}$. In Fig. 20c, the same ampere-turns excitation is required, but control current provides part of the I_{ex}, and $\bar{I}_{ex} = \bar{I}_2 + \bar{I}_c$, with all current referred to one base. Still $I_2 + I_R = I_1$ and Fig. 20c shows that I_R must now be of increased magnitude. This means that the control current for this condition is such that the IR drop is greater with control current than without.

Similar reasoning may be applied to the effect of control current in the secondary of CPT_1 with I_1 at unity power factor (with respect to V_1).

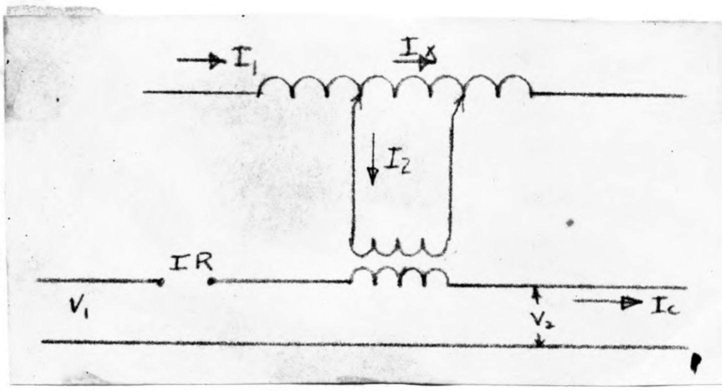
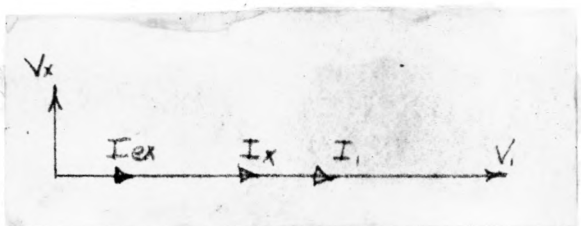


Fig. 21a



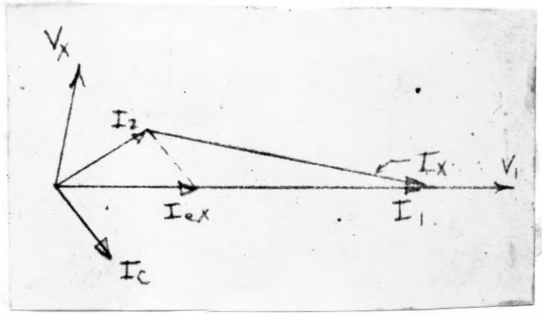


Fig. 21b. Without I_c. Fig. 21c. With I_c.

Now it is seen in Fig. 21c that the I_x is shifted so as to lag slightly the I_x in Fig. 21b. Also the vector I_x is slightly longer. The shifting of I_x has the same effect as adding a resistive component while the increase of magnitude in I_x further increases the I_x drop. Both of these, in general, will cause V_1 to increase for a given V_2 of 120 volts. This was experienced in testing the circuit with and without the control current. It should be remembered, however, that much of control current error was corrected by reducing this current from 145 to 21 ma, as explained in Part I of this thesis.

Modification of the Line Drop Compensator

It is possible to achieve some very close corrections with respect to errors present in the line drop compensator. However, the best methods of correction from the standpoint of performance are not always feasible from the standpoint of space or economics.

Error Due to Exciting Current in CPT_1 and CPT_2. First of all, the phase shift of the IR drop caused by the excitation current (as explained previously) in CPT_2 was corrected as follows. Excitation current in Fig. 17b amounts to about 0.35 ampere with 24 volts on the dial, and this current is lagging $I_R R_{var}$ by about 80 degrees. In order to make $I_R = I_1$ in both magnitude and angle, I_{ex} can be virtually cancelled with the addition of a parallel capacitor either across the primary or the secondary of CPT_2. Of course, it is impractical to place the capacitance across the low-voltage primary when the low-voltage side would require 25 times the capacitance value of the high-voltage side to achieve the same effect. Then to nullify the I_{ex} current, let $X_c = X_L = V/I_{ex} = \frac{24}{0.07}$. Here I_{ex} of 0.35 ampere is referred to the high-voltage side by a 5 to 1 turns ratio. Then $X_c = 340$ ohms and C = 7.8 mf. The circuit was then tested with 8-mf capacitance placed across points 4 and 5 (CPT_2 secondary). At 0.809 power factor with R = 24 and X = 0, the 8-mf capacitance dropped the voltage V_1 by about 1.4 volts as expected.

The CPT_1 of the particular unit under test was compensated to lower the IX voltage reading across points 6 and 7 to equal the dial setting. This meant reducing the turns in the high-voltage side from 216 to 194 turns. Actually, a reactor core gap adjustment will also give compensation, and, in fact, this is done on X_{var} during manufacture before varnish dipping of the core and coils.

Eliminating the Effect of Resistance in X_{var}. Eliminating the R in X_{var} was more of a problem. Of course, the R in X_{var} was nearly proportional to the amount of X. Several approaches might be used here. For example, one method of correction might be to place a variable resistor (R_x) in series with R variable which is equal to the R in X. R_x and X_{var} would need to be varied with a common dial in such a way that when X_{var} is maximum, R_x is minimum, and vice versa. (See Fig. 22.) This means, of course, that with rated I, there is always 2 volts IR as a minimum value, even when $R_{var} = 0$. This would require that R_{var} dial would start at 2 volts instead of zero, but it would offer excellent compensation for the R in X_{var} at all settings of the X_{var} dial. A zero setting would be obtained by shorting leads 4 and 5.

Another method which would correct for the R in X is shown in the diagram of Fig. 23. Here it is seen that the potential transformer (CPT_1) has been eliminated. At the same time, secondary windings have been added to the X_{var} reactor for the purpose of reflecting the reactance voltage into the sensing circuit. This method of picking off the voltage will give more

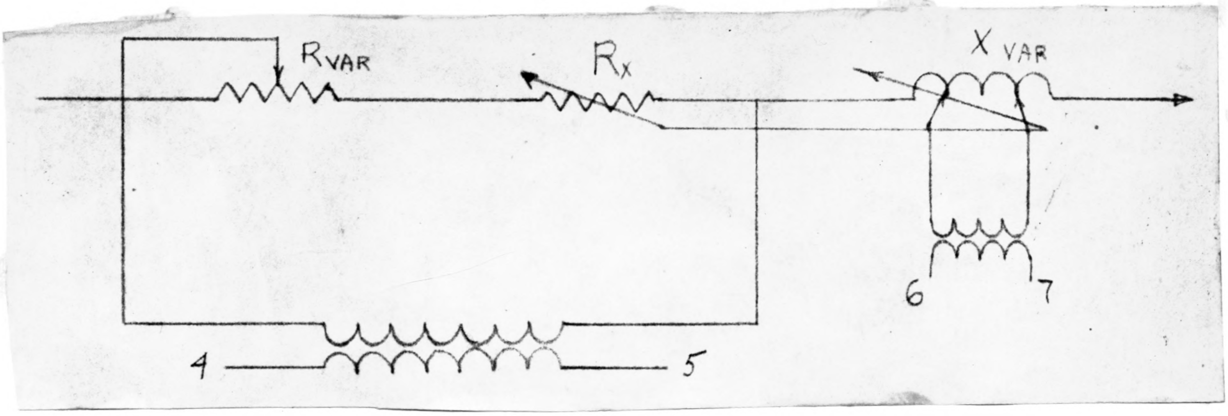


Fig. 22.

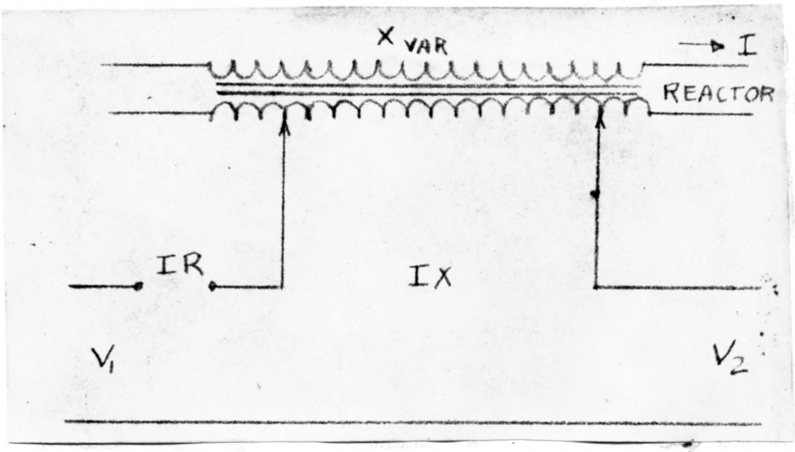


Fig. 23.

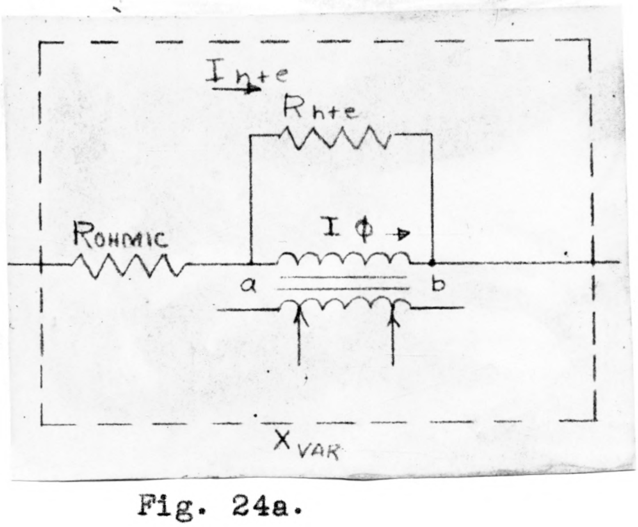


Fig. 24a.

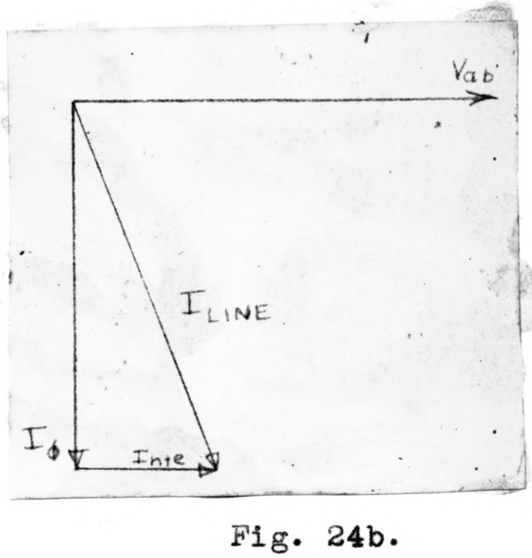


Fig. 24b.

nearly a pure reactance voltage since the reactor secondary will indicate only the rate of change of flux in the core. The ohmic resistance voltage of X_{var} will for the most part be missing from the secondary voltage. Of course, the core loss branch (R_{h+e}) will cause some slight error as it shifts the voltage V_{ab} away from I_{line} by something less than 90 degrees, as shown in Fig. 24b.

The way which was chosen to correct for the R in X was an indirect approach which gives correction under one condition but not under another. In other words, it was determined what the most likely dial setting would be, and correction was aimed first for those conditions. For example, with R_{var} and X_{var} both set on 24, it is realized that I_x contains 2 volts of IR voltage. One obvious compromise was then to remove 2 volts of IR from R variable at the maximum setting of the R dial. In other words, let the R dial read 24 volts but measure only 22 behind the panel (between points 4 and 5). Of course, if only X is set on 24, the error due to R in X is still present, but this condition of only 24 volts line reactance is unlikely to occur. Actually, the potential transformer (CPT_2) was compensated to read about 21 volts at the 24-volt setting, to include about one volt correction due to control current effect. This correction requires taking out 4/25 x 234 = 37 turns. (CPT_2 had been overcompensated to give 25 volts IR at the 24-volt setting.)

Summary of Part II

To summarize the modifications on the line drop compensator, the following changes were made.

1. The turns of the high-voltage winding in CPT_1 were reduced from 216 to 194 turns in order for V_{6-7} to equal 24 volts when the X dial is set on 24.

2. The turns of the high-voltage winding in CPT_2 were reduced from 234 to 197 turns, in order for V_{4-5} to equal 21 volts when the R dial is set on 24.

3. An 8-mf capacitor was placed across the secondary of CPT_2 (points 4 and 5).

The result of the above changes may most readily be seen by comparing curves of Figs. 56 and 57. Here it is seen that when R_{var} and X_{var} are both on the same dial setting, the measured and calculated curves rise very close together, both for 0.809 power factor and for 0.996 power factor. Some error is still present with only X_{var} and also with only R. However, as was mentioned before, step 2 above was merely a compromise method to obtain best results for the condition of both R and X dials at equal settings. At the setting of R = X = 24 and power factor = 0.809, the variation between calculated and measured values for V_1 was reduced from 8.8 volts to 1.5 volts. With a power factor of 0.996 this variation in V_1 was reduced from 4.4 volts to about 0.4 volt after modifying the circuit.

PART III. PARALLELING CONSIDERATIONS

Basic Theory

Some basic requirements for satisfactorily paralleling transformers are given as follows: (1) Same voltage ratings, (2) same turns ratio, (3) same per cent impedance based on the individual kva ratings, (4) equal ratio of r_e/x_e, where r_e and x_e are the equivalent transformer resistance and leakage reactance, respectively.

A simplified schematic is shown in Fig. 25 which represents two equally rated transformers connected in parallel feeding a common load through the line impedance (Z_L).

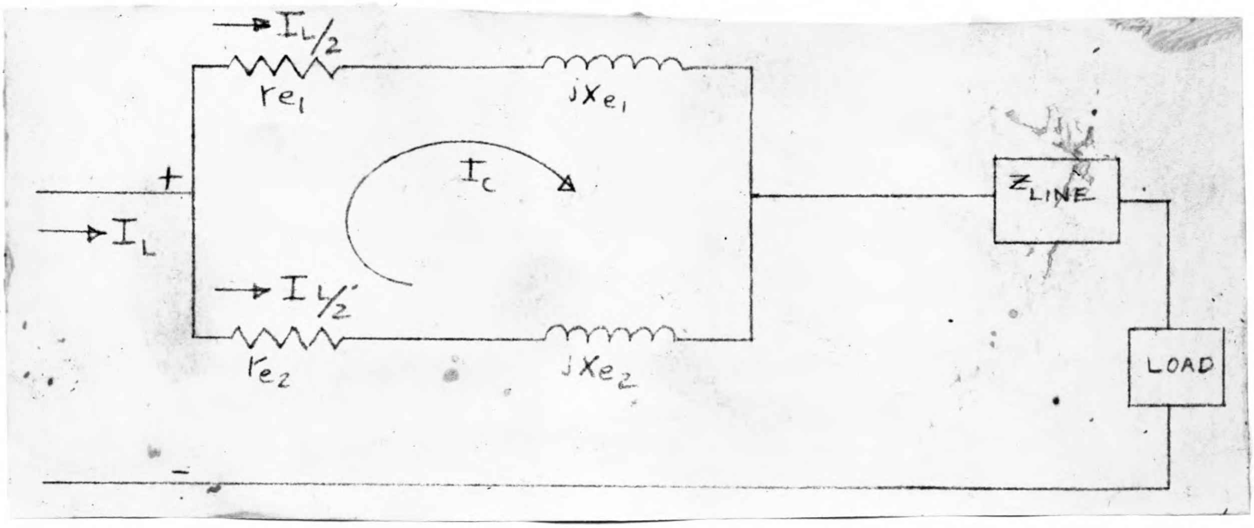


Fig. 25. Circulating current due to unequal transformer impedances.

The currents in transformer No. 1 and No. 2 divide inversely as their impedances, or $I_1 = I_2 \frac{Z_{e2}}{Z_{e1}}$. When Z_{e1} and Z_{e2} are unequal, I_1 and I_2 relations can be written as follows:

$$I_1 = I_L \frac{Z_{e2}}{Z_{e1} + Z_{e2}}$$

circulating current

$$I_c = I_1 - \frac{I_L}{2} = I_L \left(\frac{Z_{e2}}{Z_{e1} + Z_{e2}} - \frac{1}{2}\right) = I_L \frac{Z_{e2} - Z_{e1}}{2(Z_{e1} + Z_{e2})}$$

Even when impedances are equal, turns ratios may be unequal. This will have the effect of producing a circulating current in the transformers which is set up by the voltage difference of transformers No. 1 and No. 2. It is assumed here that unit No. 1 is of higher voltage than No. 2. This voltage increment is represented in Fig. 26 as E_c.

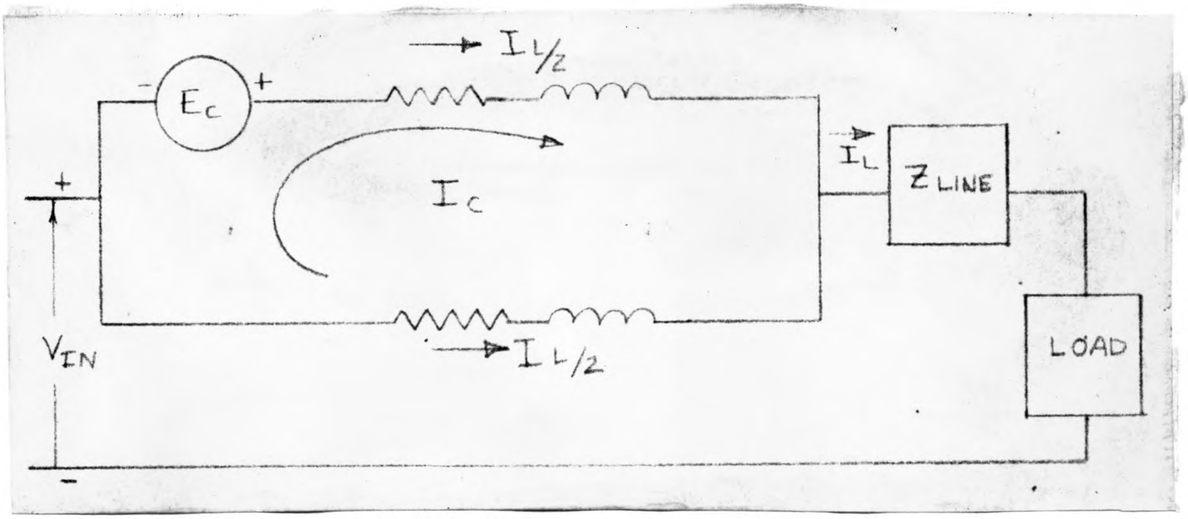


Fig. 26. Circulating current due to unequal turns ratio.

E_c will be nearly in phase with V_{in} but will feed I_c through twice the impedance of one transformer. This impedance which I_c moves through is essentially reactive since $X >> R$ for transformers in the large power sizes. This means that circulating current contains a large quadrature component with respect to E_c and V_{in}. This fact is used later on in connection with the circulating current method of paralleling transformers. However, circulating current caused merely by unequal transformer impedances will be more nearly in phase with load current even when Z_{e1} and Z_{e2} are essentially reactive. This can be reasoned from the equation of

$$I_c = I_L \frac{Z_{e2} - Z_{e1}}{2(Z_{e1} + Z_{e2})}$$

by letting Z_{e1} and Z_{e2} be purely reactive, which puts I_c in phase with I_L.

Two problems stand out above others in paralleling LTC transformers. First, when circulating current increases because one transformer is set for higher voltage, this extra current in one unit would increase the IZ drop in the line drop compensator of the higher circulating current unit. Then if no correction is made, this condition serves to further increase circulating current. This results in the driving of one tap changer to one extreme ratio while driving another unit to the opposite extreme.

The other problem in paralleling shows up when one unit is removed from service. For a given load, the remaining transformers must take on the added load current of the idle unit. Each line drop compensator would see this added load current, thus increasing the IZ_L drop of each unit. This is not desirable, since neither the line impedance (Z_L) nor the line current has changed.

Methods of Paralleling

Some of the methods of handling the problems of paralleling in LTC transformers are as follows:

1. Reverse reactance
2. Cross current compensation
3. Circulating current (also called current balance)
4. Electrical interlock
5. Mechanical ties.

This thesis will deal with the first three methods.

Reverse Reactance. To cover the reverse reactance method of paralleling, refer to Fig. 27. Provisions are made to reverse the secondary leads of CPT_2 (points 6 and 7) for the purpose of reversing the IX drop of the line drop compensator when paralleling with another unit. Then any increase in circulating current

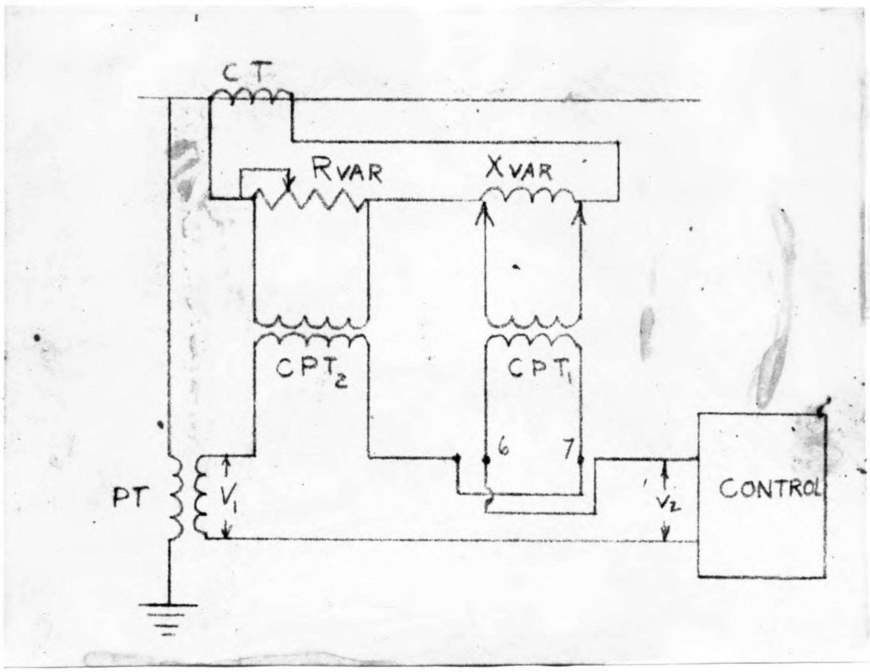


Fig. 27.

in one unit shows up as a decrease in total IZ drop. The control circuit will then act to decrease the voltage of this unit, thereby reducing the circulating current.

Again it is recalled that circulating current is reactive with respect to V_1. If we assume I_c lags V_1 by 90 degrees (Fig. 28), then jIX is back in phase with V_1 (or 180 degrees

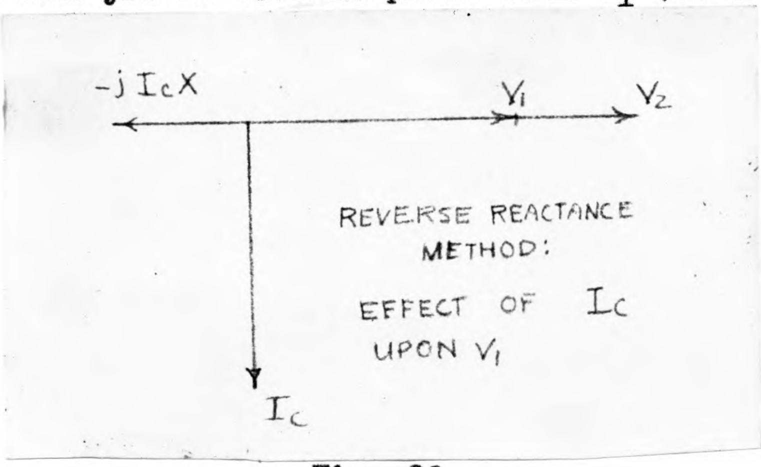


Fig. 28.

out of phase, depending upon whether or not reactance is reversed). A disadvantage of this method is that the representation of the $I_L X_L$ of the line is destroyed. Another disadvantage is that with low power factor, increasing load current would also tend to reduce the voltage V_1 (which is undesirable). Any time a quadrature current (I_q) is fed into the X elements of the line drop compensator, the jI_qX is a voltage which is almost an algebraic addition or subtraction to the vector V_2.

One advantage of the reverse reactance method is that it requires neither special control devices nor interconnection between controls of separate units. ASA Standards require LTC transformers to have provisions for reversing reactance.

<u>Cross-current</u> <u>Compensation</u>. This method of paralleling

requires that the main current transformer of unit No. 1 feed the line drop compensator of unit No. 2, and vice versa, as shown in Fig. 29. In this way any increase in current delivered by unit No. 1 would raise the voltage on unit No. 2. At the same time, the lower current of unit No. 2 will move to decrease the voltage of unit No.1.

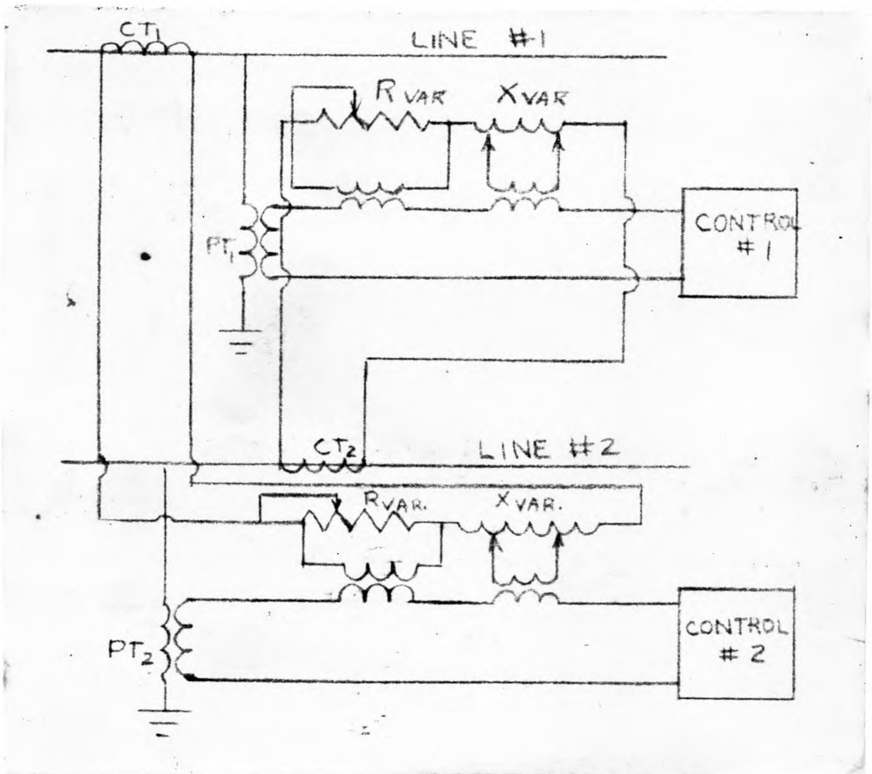


Fig. 29. Cross-current compensation.

This method is limited to two units in parallel and at the same time requires interconnection between units. Also when one unit is removed from service, it is necessary to change the control connections so that the current transformer of the unit left in service is connected to its own compensator. This system works fairly well when two transformers are located close together.

Circulating Current Method. This method is referred to by some as the "current balance" method and is satisfactory for any number of transformers in parallel. This method solves the two main problems mentioned previously which are present whenever LTC transformers are paralleled. In order to explain the methods by which these two paralleling problems are solved, the problems will be dealt with separately. Separate schematic diagrams will be shown for consideration, then the circuits combined into one final form. In each case it will be assumed that three units are paralleled. First refer to Fig. 30. The line drop compensators shown are Wagner compensators and only slight modifications of the circuits of Figs. 30, 31, and 32 would be necessary to adapt the circulating current method to circuits of other manufacturers. The letters (LCT) in Fig. 30 stand for load current transformer, also called a blocking transformer. Its purpose is to separate the load current from the circulating current. This is accomplished by connecting the secondaries of LCT transformers in series. This forces the circulating current to follow a separate path through the PX windings. The solid arrows represent one unit of load current while the dotted arrows represent circulating current. The PX windings are reactors with secondary turns. These turns are wound in such a way as to give a voltage decrease at a main transformer whenever this transformer supplies excessive circulating current due to high voltage. Of course, it will also correct for low transformer voltage in the same manner.

The circulating current method also provides for the removal of one unit from service. Without the added feature of the CCT

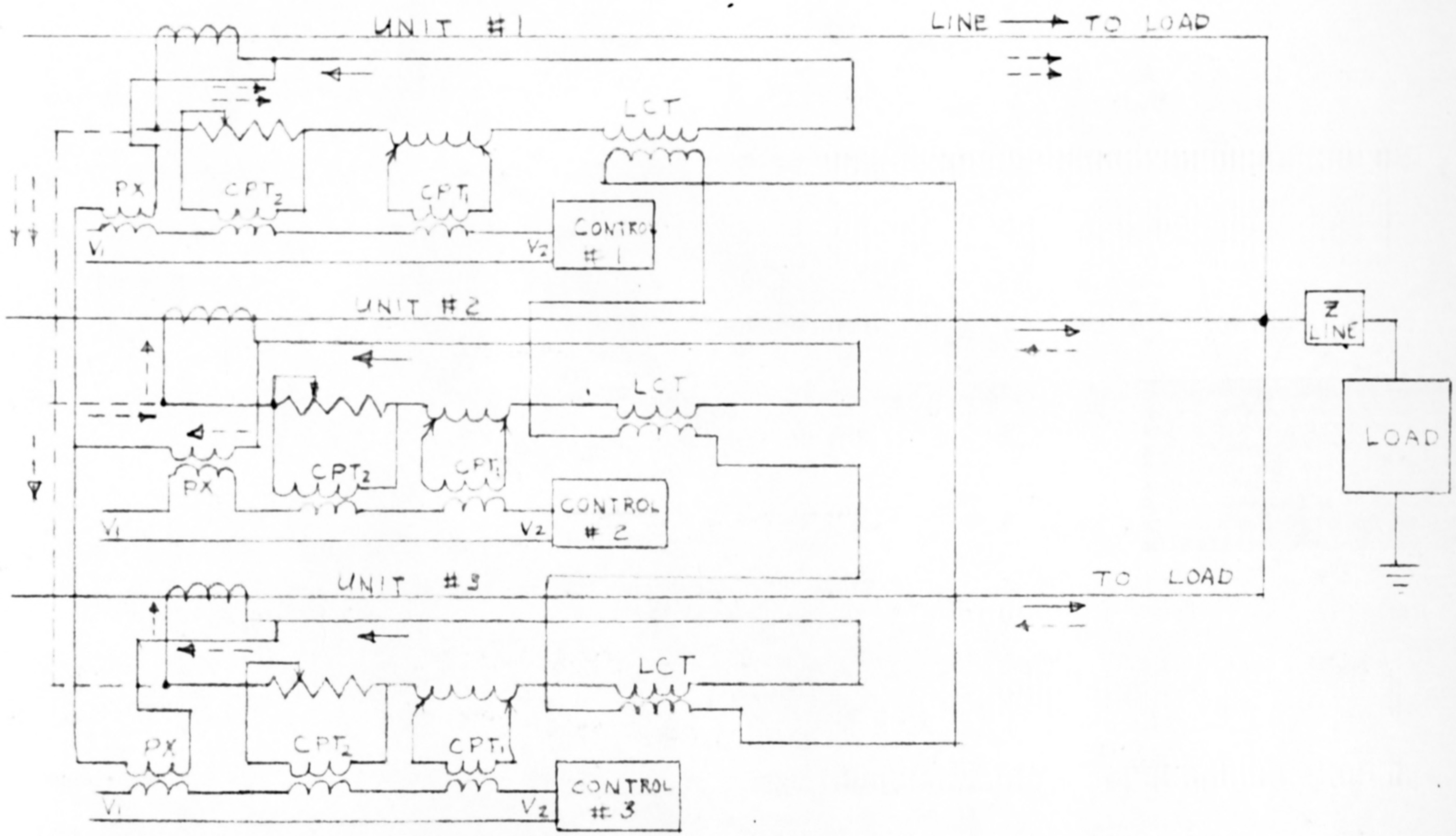

UNIT #1
LINE → TO LOAD
LCT
PX
CPT_2
CPT_1
CONTROL # 1
V_1
V_2
UNIT #2
LCT
CPT_2
CPT_1
PX
CONTROL # 2
V_1
V_2
Z LINE
LOAD
UNIT #3
TO LOAD
LCT
PX
CPT_2
CPT_1
CONTROL # 3
V_1
V_2

Fig. 30.

current transformer as shown in Fig. 31, the increased load current (picked up by the transformers remaining in service) would show a higher IZ drop in their individual line drop compensators. In reality the IZ drop of the line itself has not changed. Figure 30 shows a compensating or equalizing current transformer CCT in each unit which serves to equalize the currents in each line drop compensator. This is because the CCT secondaries are in series and will therefore carry equal current, thus forcing the primaries to do likewise. This is made possible by the addition of the dotted line connections shown.

Combining the circuits of Figs. 30 and 31 gives the final circuit of Fig. 32. Contacts marked "a" and "b" are also added. Contact "a" is normally closed and is open only when a unit is removed from service. At the same time, "b" (normally open) is closed upon removing a unit from service. Closing "b" in the idle unit allows equalizing current to flow even though the LCT primary carries no current.

Specific Notes on a Paralleling Application. Attached is parallel connection diagram (TS2382) which was proposed as the scheme for paralleling a Wagner transformer with two General Electric transformers. It was necessary here to use the ACT transformer since one line drop compensator operates on a 5-ampere basis and General Electric from a 0.2-ampere basis.

Moloney Electric has used another scheme whereby the PX windings are not star-connected, but are individually paralleled with secondaries of their corresponding LCT current transformers. This method allows both circulating and load current to

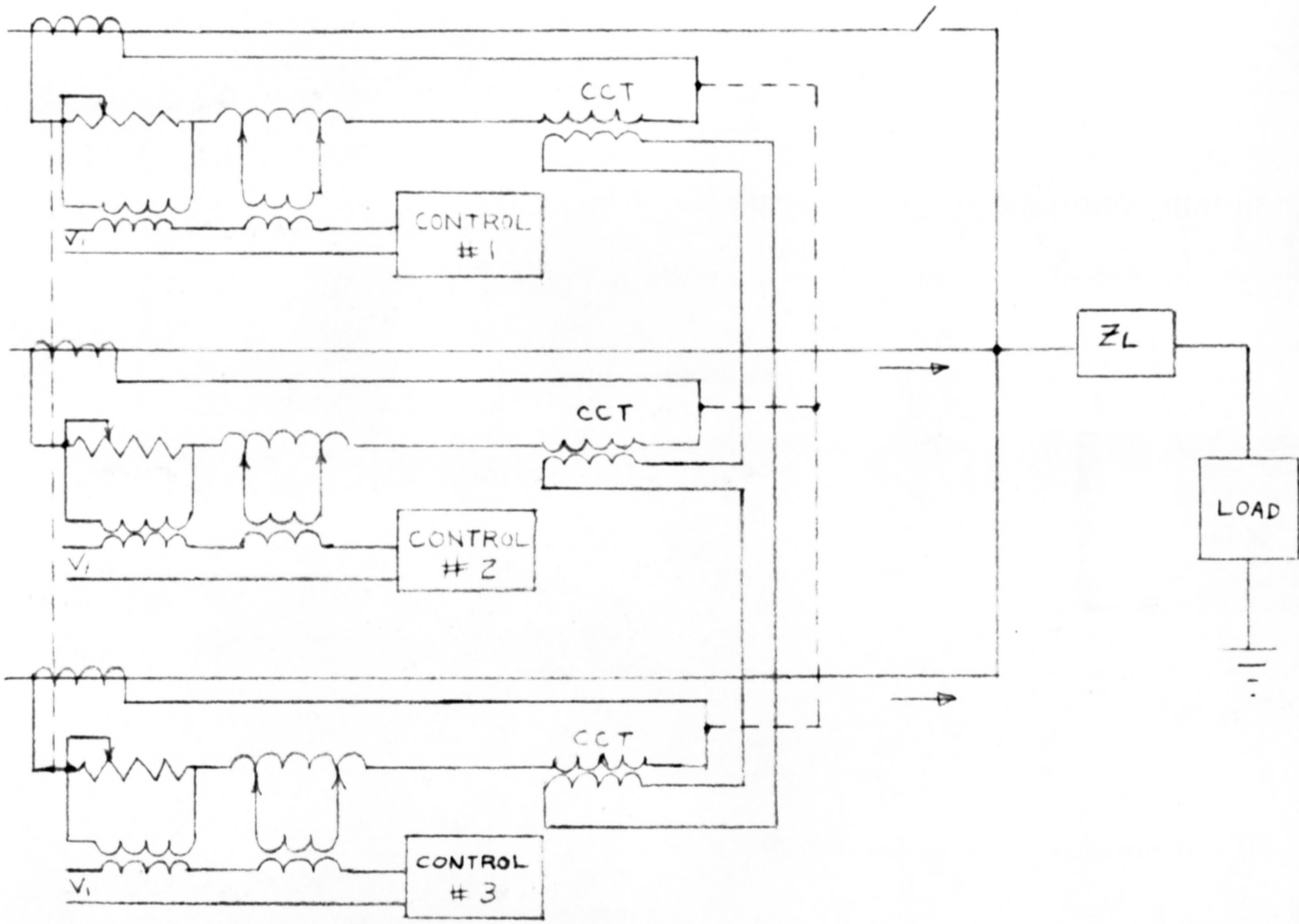


Fig. 31.

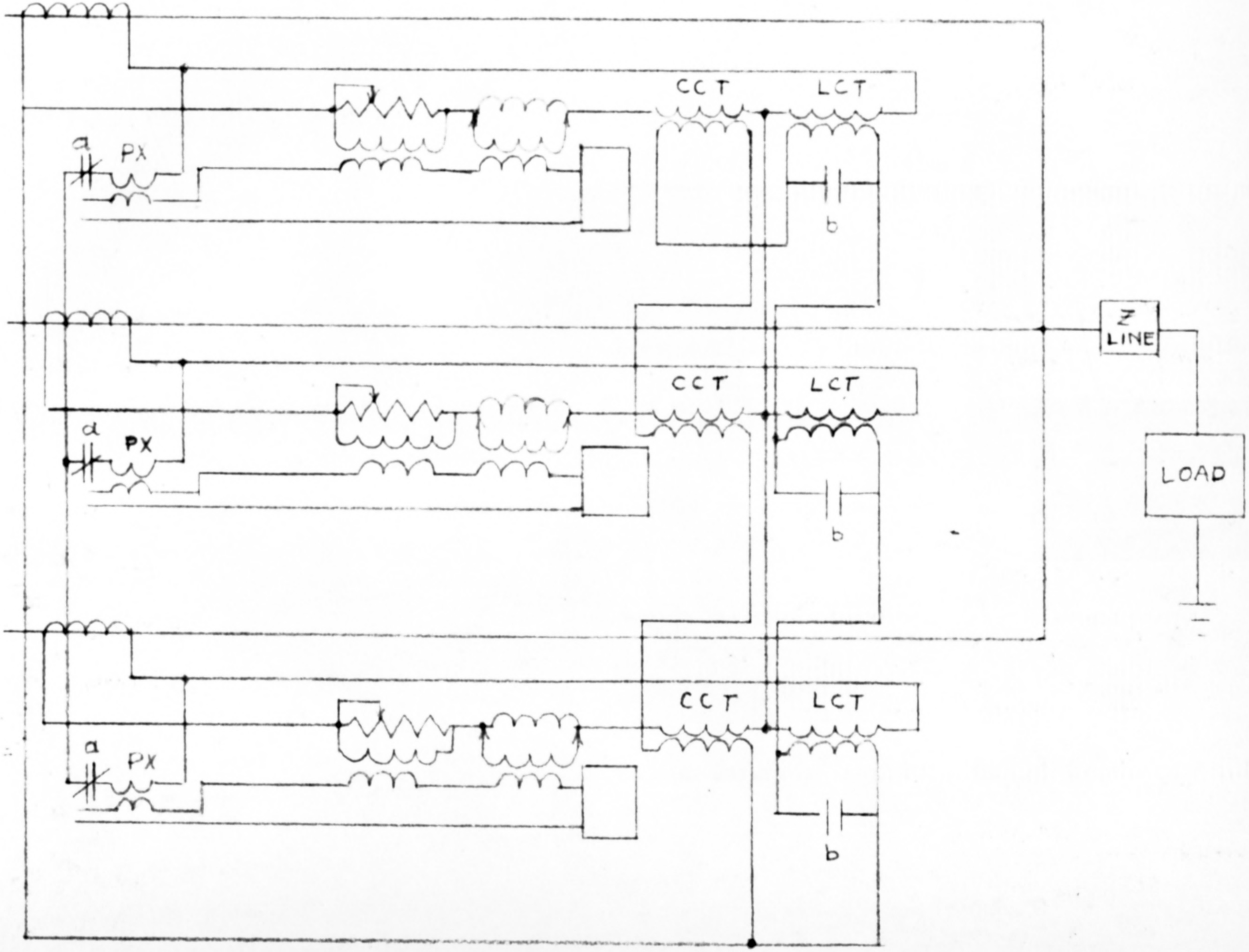


Fig. 32.

pass through the primary and secondary of LCT but the circulating current then is diverted into the PX winding for reflecting this I_cX into the line drop compensators. It may be possible to use this method in paralleling 5-ampere compensators with the 0.2-ampere compensators in the future. The advantage of paralleling the PX and LDC winding with the LCT secondaries (for TS-2382) would be in the elimination of the ACT current transformer and the "a" contacts. A disadvantage of this scheme is that the PX and LDC windings must be designed alike in order for circulating currents to divide properly, whereas the star connection for LDC and PX windings will accept proper circulating current in spite of varying reactor values. Another advantage in paralleling the PX windings with LCT secondaries lies in the fact that it is easier to step down to 5 amperes than 0.2 ampere at the main line current transformer. This could result in the saving of one more current transformer.

It is often true, as in the case of a delta or 3-wire Y-connected transformer, that some method must be employed to bring the voltage (V_1) and the line current into the proper phase relationship. For example, a delta-connected secondary will deliver a line current which is 30 degrees out of phase with line voltage when delivering a unity power factor load. The method shown in Fig. 33 will serve to show the proper magnitude and phase angles for voltage (V_1) and line current which appear in the line drop compensator circuit. This is accomplished as shown by the vector diagram which takes the difference of two currents to bring the current in phase with the line voltage (for unity power factor loading). See Fig. 34.

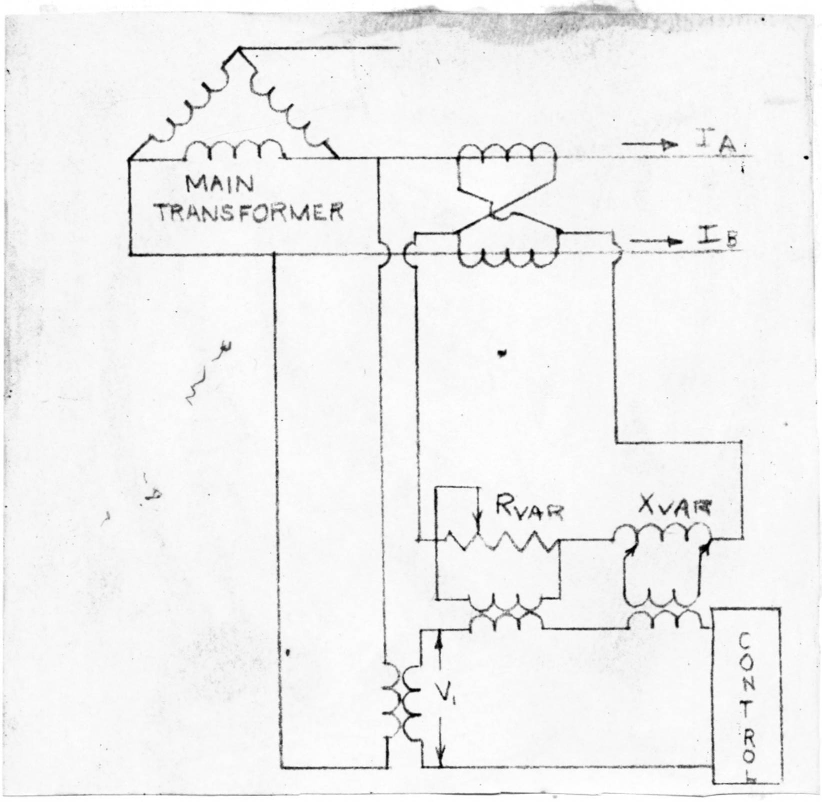


Fig. 33.

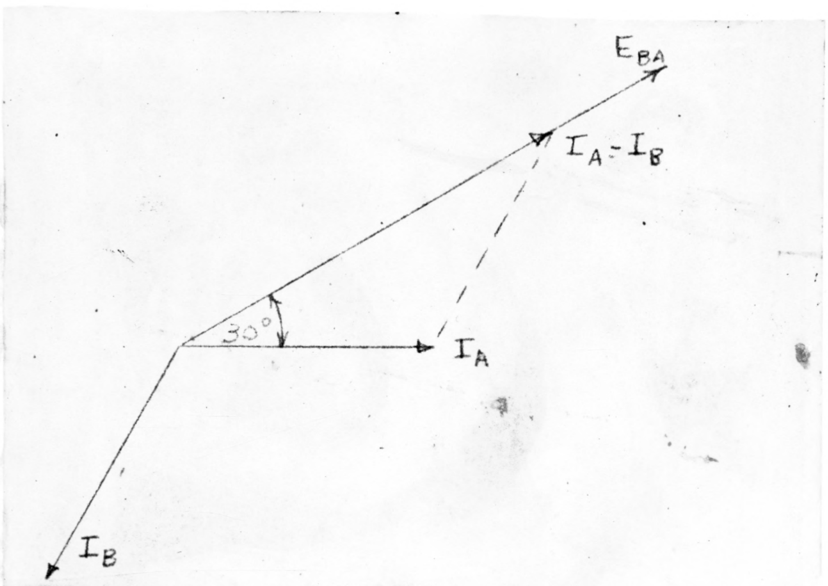


Fig. 34.

For the most part, each paralleling problem will require individual attention in arriving at a satisfactory circuit. This will be up to the transformer engineer to meet customer specifications with regard to the method of paralleling. Also, whenever an LTC transformer is to be designed for paralleling with a unit or units supplied by another manufacturer, the standard data (turns ratio, per cent impedance, etc.) must be obtained from this manufacturer. In addition, special information (pertaining to their LTC control unit) and provisions for paralleling must be obtained.

ACKNOWLEDGMENT

The writer acknowledges his indebtedness to many people who were of great assistance in the writing of this thesis. Mr. Jack Dudley, of the Wagner Electric Corporation, outlined much of the project as it was studied. Mr. William McCarty, also of the Wagner Electric Corporation, assisted in the experimental research. Professor Melvin C. Cottom was most helpful in his suggestions as major adviser. Appreciation is extended also to Mrs. Lola Crawford for her efficient service in the typing and assembly of the thesis.

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APPENDIX

AUTOMATIC CONTROL EQUIPMENT - - Control Instruments

Fig. 35.

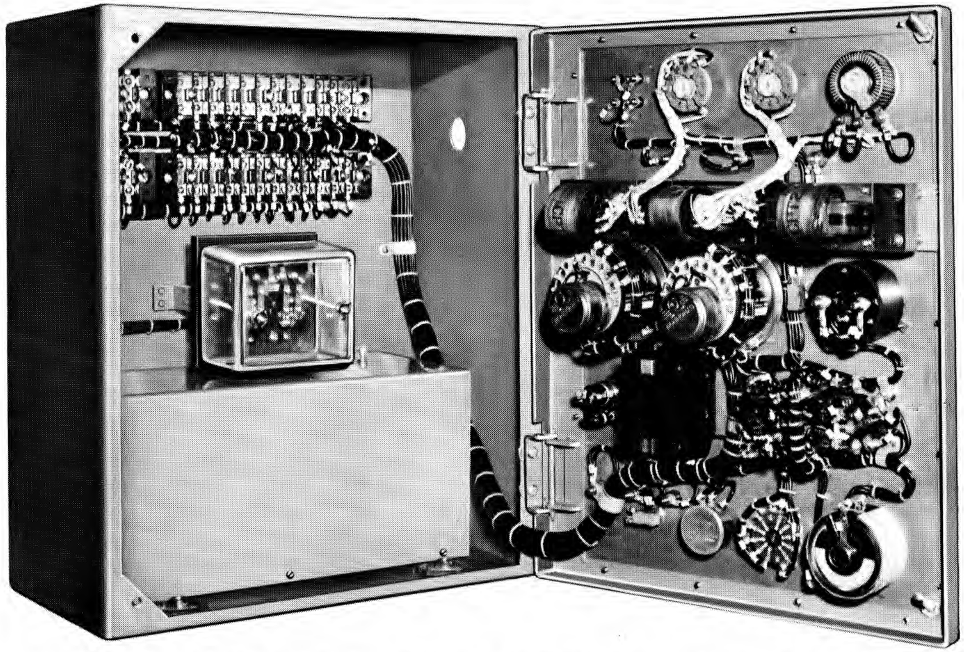


Photo 17087A — Interior of Control Instrument Cabinet

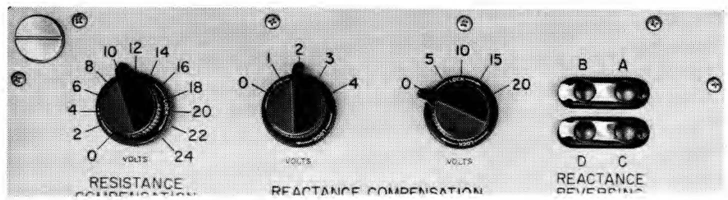
The automatic control instruments include:

A. Time Delay Equipment

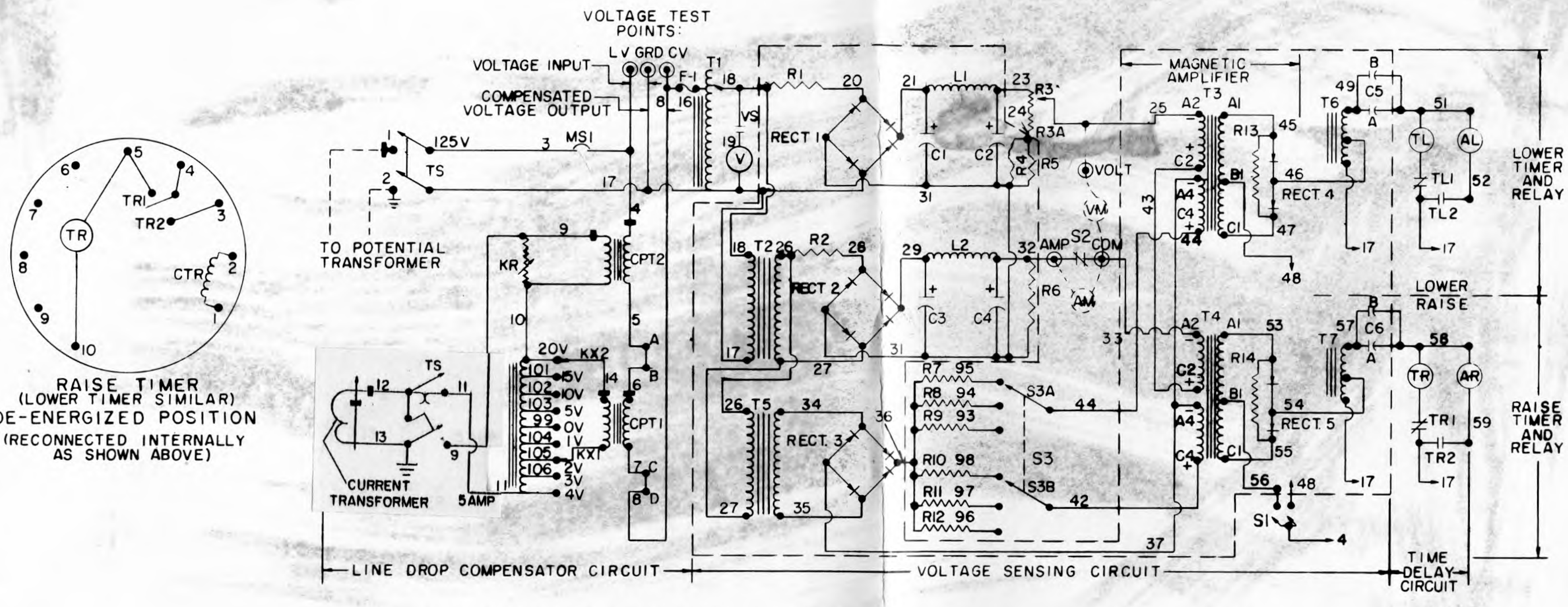
B. Voltage Sensing Equipment

C. Magnetic Amplifier Voltmeter

D. Band Width Selector



TE-8778B — LTC Control Wiring Diagram



IDENTIFICATION OF COMPONENTS

AL — Auxiliary Relay (Lower)
AL_1, AL_2, AR_1, AR_2, — Auxiliary Relay Contacts
AR — Auxiliary Relay (Raise)
AT — Auto Transformer
B — Brake
C_1 to C_7 — Capacitors
CO — Convenience Outlet
CPT_1, CPT_2 — Compensator Transformers
CSAM — Control Switch, Automatic Off Manual
CSRL — Momentary Switch Spring Returned from Raise or Lower to Off
CTL — Lower Timer Clutch
CTR — Raise Timer Clutch
DSI — Door Switch, Closed When Door is Open
F_1, F_2 — Fuses
H — Heater
HS — Heater Switch
IS — Micro-Switch, Normally Closed, Open When Hand Crank is Used
KX — Variable Compensator Reactor
KR — Variable Compensator Resistor
KX_1, KX_2 — Compensator Switches (Reactor)
L_1, L_2 — Chokes (Filter)
LSL_1, LSL_2 — Lower Limit Switches
LSR_1, LSR_2 — Raise Limit Switches
LT — Light, Control Compartment
M — Motor
ML — Motor Starter Coil (Lower)
ML_2, ML_3, ML_4 — Motor Starter Contacts (Lower)
MR — Motor Starter Coil (Raise)
MR_1, MR_2, MR_3, MR_4 — Motor Starter Contacts (Raise)
MS_1, MS_2 — Thermal Air Breakers, Control Potential & Motor Circuits
PSL_1, PSR_1, PS_2, PS_4 — Pilot Switches
R_1 to R_{14} — Resistors
RL — Red Light On Indicates Tap Changer Between Tap Positions
S_1 — Time Delay Switch
S_2 — Ammeter Shunt Switch
S_3 — Band Width Selector Switch
RECT. 1, 2, 3, 4, 5 — Rectifiers
T_1 — Variable Voltage Control
T_3, T_4 — Magnetic Amplifiers
T_2, T_6, T_7 — Transformers
T_5 — Constant Voltage Reference Transformer
TL — Timer Lower Motor
TL_1, TL_2 — Timer Lower Contacts
TR — Timer Raise Motor
TR_1, TR_2 — Timer Raise Contacts
TS — Test Switch Assembly
V — Voltmeter
VS — Voltmeter Switch
LV, CV, GRD. — Test Terminals, Compensator
TB_1, TB_2, TB_{3A}, TB_4, TB_5 — Terminal Blocks
AMP, COM, VOLT — Test Terminals, Magnetic Amplifier

NOTES

1. The exact layout of Wires, Apparatus or Cables may not be as shown.
2. Apparatus is shown de-energized & in the Neutral Position.
3. When the Tap Changer is on position, Pilot Switches PSL_1 & PSR_1 are closed but open immediately after PS_2 closes.
4. When Tap Changer is on position, Pilot Switches PS_2 & PS_4 are open but close immediately after the Tap Changer rotates a few degrees & opens immediately before reaching the next position.
5. At extreme Lower position the normally closed LSL_1 & LSL_2 Switches open.
6. At extreme Raise position the normally closed LSR_1 & LSR_2 Switches open.
7. When Time Delay is desired between each Tap Change, connect 71 to 73 on TB_2, as shown.
8. When Time Delay is desired on First Tap Change only & no Time Delay desired on following Steps until Voltage is corrected, connect 71 to 62 on TB_2 instead of 71 to 73.
9. Turn MS_1 Switch off before changing Timer setting.
10. Normal Reactance Compensation: Connect A to B & C to D as shown.
    Reverse Reactance Compensation: Connect A to C & B to D.
11. The Circuit from Points 62 and 64 through Contacts on Reclosing Relay, when used, is for the purpose of preventing Tap Changer operation during the time a Line Fault is sensed by the Relay. If such a Relay is not used Connect 62 to 64.

Fig. 36.

EXPERIMENT No. 1

<u>Purpose</u>: To determine the shapes and magnitudes of current in the "original" control circuit. The circuit sketch is shown below. Refer to TE-8778-B, Fig. 36, for more complete drawing.

<u>Diagram</u>:

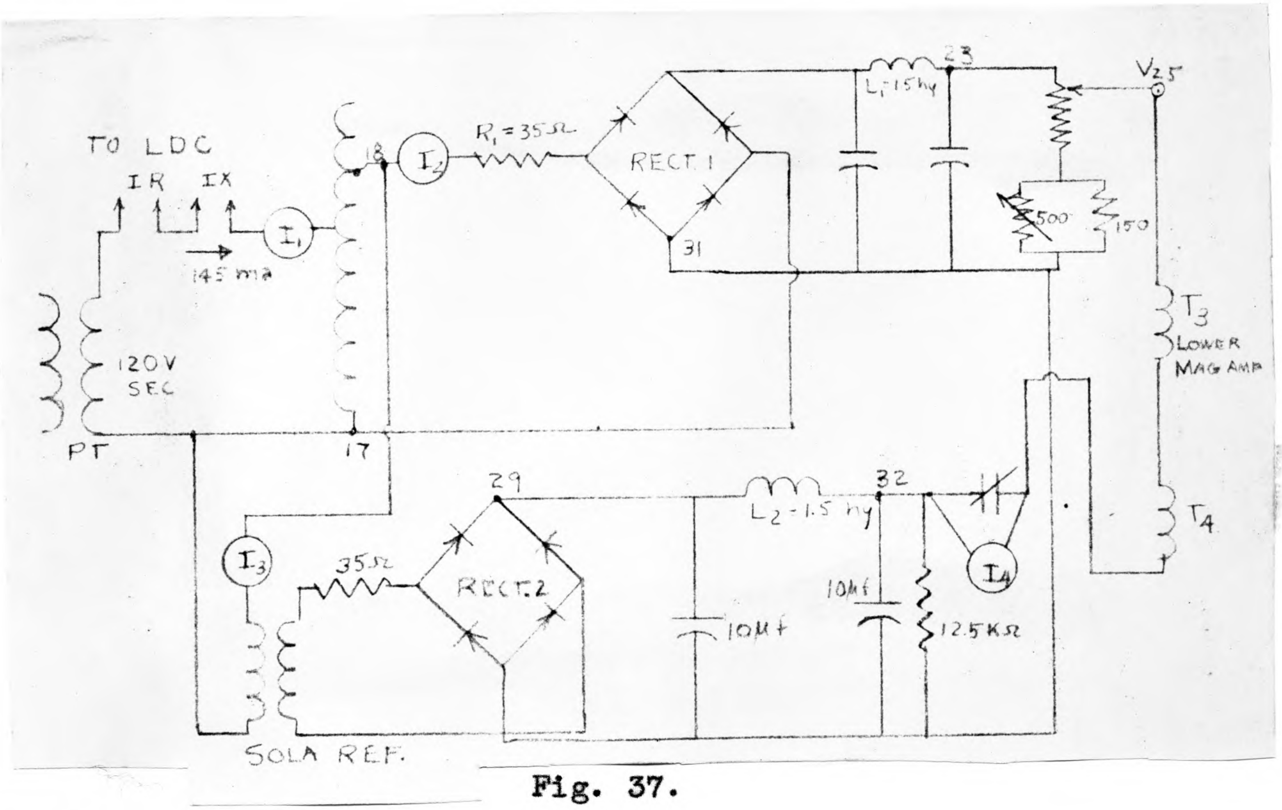


Fig. 37.

<u>Procedure</u>:

I A. Set V17-18 at 120 volts. Balance the current (I_4) to zero, using the "amp adjust" resistor to vary volts at point 25. Measure V_{18}, V_{23}, V_{26}, V_{32}, I_1, I_2, I_3, I_4. Also measure exciting current taken by T_1.

B. Picture I_2 and a-c ripple of voltage V_{23} on the oscilloscope under conditions of Part I-A.

C. Measure a-c line current flowing into the magnetic

EXPERIMENT No. 1 (con't.)

amplifiers when (a) clock is running, and (b) relay is closed.

II A. Replace L_1 and L_2 with 9-henry chokes. Remove C_1 and C_2. Again measure voltages and currents listed in I-A of Procedure.

B. Picture I_2 and a-c ripple of voltage (V_{23}).

III A. Move Sola lead 18 over from top of T_1 to point 3. Keep choke input filter as in II-A. In order to balance I_4 with "amp adjust" at about mid-tap, it is necessary to tap down about 1800 ohms on the output bleeder resistor of the reference circuit. Record V_{23}, V_{amp}, and I_1.

<u>Data</u>:

Date: <u>6-8-60</u>

I-A: V_{18} = 120 volts; I_1 = 145 ma; I_3 = 128 ma

V_{23} = 165 volts; I_2 = 33 ma; I_4 = 0

V_{32} = 143 volts; I_{ex} to T_1 (unloaded) = 63 ma

I-B:

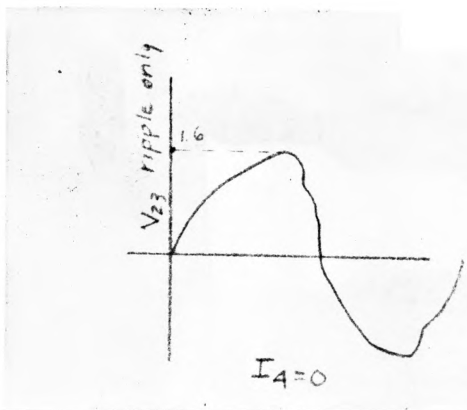


Fig. 38(a).

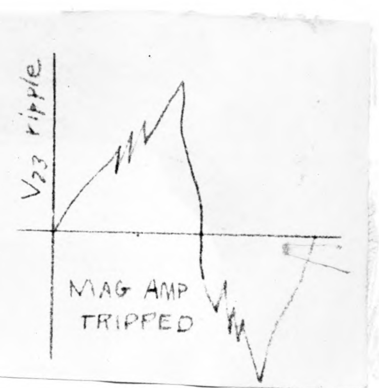


Fig. 38(b).

EXPERIMENT No. 1 (con't.)

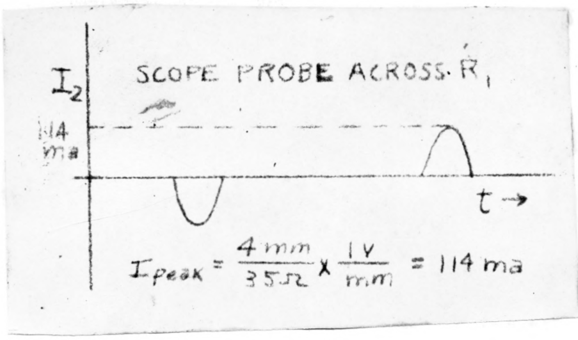


Fig. 38(c).

I-C:

	Raise Timer and relay	Lower Timer and relay
Clock current	82 ma	87 ma
Relay current	90 ma	93 ma

Date: 6-9-60

II-A: V_{18} = 120 volts; I_1 = 132 ma; I_4 = 0

V_{23} = 104 volts; I_2 = 22.5 ma

V_{32} = 109 volts; I_3 = 112 ma

Scope probe across R_1: $I_{2_{max}} = \dfrac{1.38\ \text{volts}}{35\ \text{ohms}} = 39.5$ ma

II-B

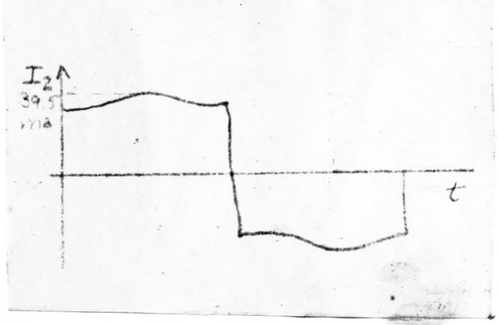


Fig. 39(a).

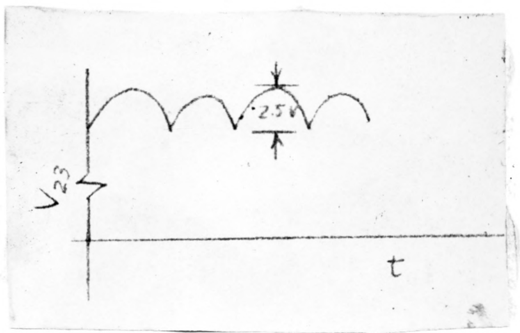


Fig. 39(b).

EXPERIMENT No. 1 (con't.)

Date: 6-15-60

III-A: V_{23} = 102 volts; $V_{reference}$ = 127 volts

V_{amp} = 92 volts; I_1 = 80 ma

EXPERIMENT No. 2

Purpose: To determine how constant the reference (Sola) voltage may be maintained with Sola lead No. 18 transferred to point 3.

Procedure:

I A. Open the "amp" switch to magnetic amplifier control winding. Apply a variable voltage to the reference circuit at points 17-18. Use the 115-volt Sola rated at 15 va. Measure the d-c voltage output of reference filter, and the secondary a-c voltage of Sola secondary with various voltages applied.

B. Repeat I-A except load the Sola with an additional 2000 ohms across the secondary.

II A. Use a different Sola rated at 118 volts (presently used in practice) and repeat test I-A. In order to obtain better accuracy in filter output variation, measure the filter output voltage by using the sensing circuit as a constant supply and bucking the reference circuit against this constant supply. See the circuit in Fig. 40. The constant supply is obtained by using an additional Sola to feed the sensing circuit. The difference between the

EXPERIMENT No. 2 (Con't.)

constant supply and the reference output will be called V_x.

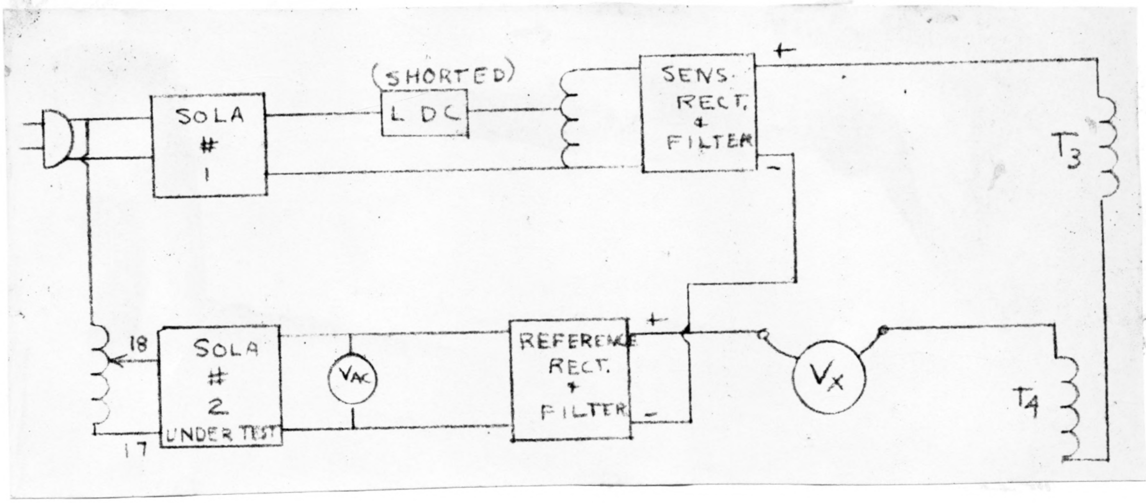


Fig. 40.

II B. After plotting curve, determine Sola input voltages which cause output to best level off. Add an autotransformer ahead of Sola if necessary which brings the voltage to this range.

Experiment No. 2 (con't.)

Table 1. Data for Experiment No. 2.

	V_{17-18}	$V_{ac\ out}$	V_{dc}	V_{17-18}	$V_{ac\ out}$	V_{dc}
Date: 6-15-60						
I-A:	10	25	19	100	125	106
	20	57	50	105	125	106
	30	97	83	110	125.5	106.3
	40	112	94.5	115	126	106.5
	50	117.5	100	120	126	106.5
	60	120	101.5	125	126	106.8
	70	122	103	130	126	106.8
	80	123.5	104	135	126	106.8
	90	124	105	140	126	106.8
	95	124	105.5	145	126	106.8
I-B:	10	19	14.3	95	120.5	101.5
	20	39.5	32.5	100	121	102
	30	63.5	53.5	105	121.5	102.3
	40	87	74	110	122	102.8
	50	104	88.5	115	122.2	102.8
	60	112.5	95	120	122.5	103
	70	116.5	98.8	125	122.5	103
	80	118.5	100	130	122.5	103
	90	120	101.3	135	122.5	103

Date: 6-16-60

	$V_{ac\ in}$	V_x	$V_{ac\ in}$	V_x	
II-A:	63	.025	115	.695	
	70	.251	120	.66	
	80	.493	125	.62	
	90	.633	130	.57	Curves on Fig. 40
	95	.685	135	.51	
	100	.700	140	.44	
	105	.700	145	.37	
	110	.700			
II-B:	65	.06	115	.508	
	70	.158	120	.515*	
	80	.300	125	.513	120/105 autotransformer
	90	.393	130	.510	ahead of Sola No. 2
	95	.435	135	.495	
	100	.465	140	.483	
	105	.485	145	.465	
	110	.495	150	.438	

*Levels off here.

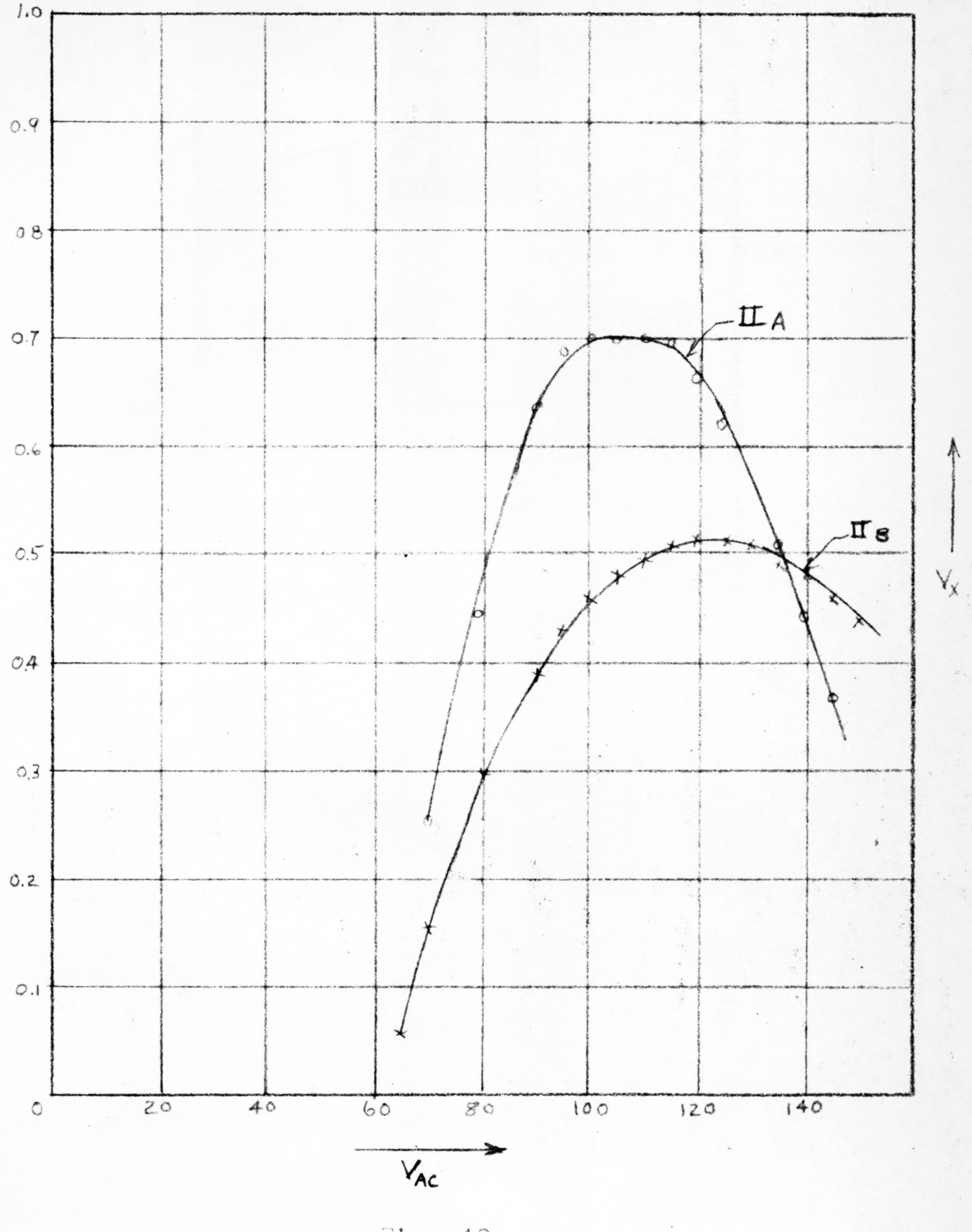


Fig. 40a.

EXPERIMENT No. 3

Purpose: Add new variac-autotransformer arrangement to replace T_1 for purpose of further reducing current through LDC and test as follows.

Diagram:

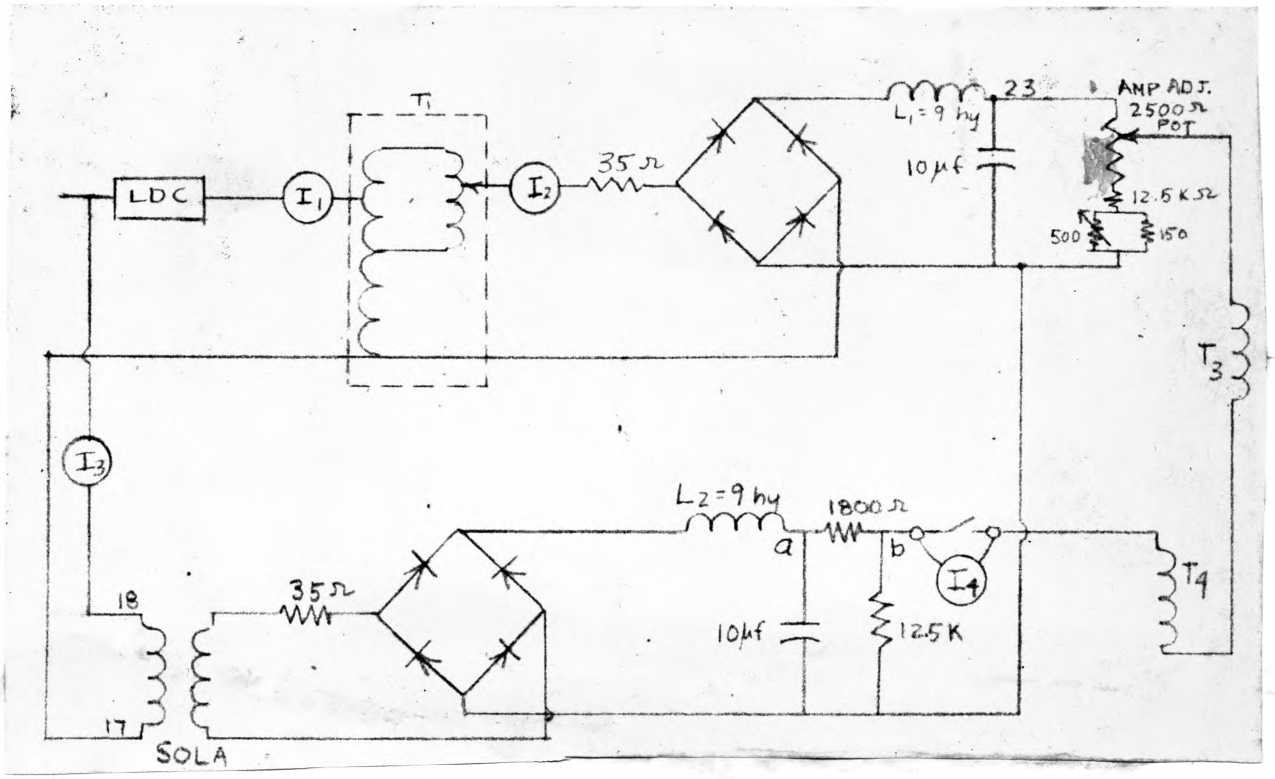


Fig. 41.

Procedure:

I A. Apply 120 volts to variac-autotransformer combination shown (dotted) on the diagram. Measure exciting current of this combination with secondary open circuited.

B. Incorporate changes into the "original" circuit, as shown in the diagram. These are (1) use of choke input filter, (2) tapping down 1800 ohms on reference bleeder, (3) move Sola input to point 3, and (4) use of variac-autotransformer

EXPERIMENT No. 3 (con't.)

arrangement to reduce excitation current. Take readings of I_1, I_2, I_4, V_{23}, V_a, V_b.

C. Picture the following currents and voltages on the oscilloscope: $V_{Sola\ out}$, I_1, and I_2.

Data:

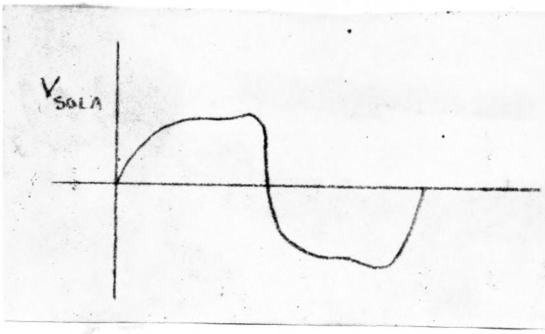
I-A: $I_{ex} = 10.9$ ma

I-B: $I_1 = 21$ ma $V_{23} = 105$

$I_2 = 13$ ma $V_a = 107$

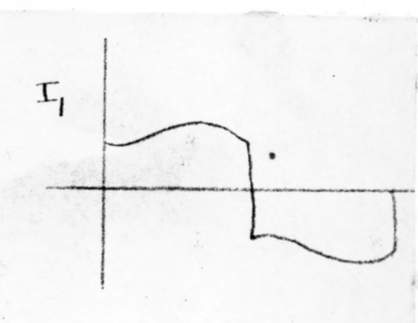
$I_4 = 0$ $V_b = 93$

I-C:



Note: Sola output becomes essentially sinusoidal when an additional 1000-ohm load is placed across secondary.

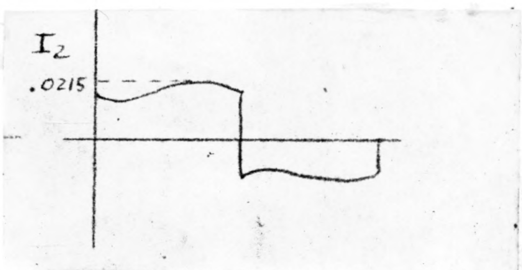
Fig. 42(a)



$$I_{1_{max}} = \frac{V_R}{R} = \frac{3.8}{50} = \frac{1}{2} = .038$$

(3.8 min x 10 V/cm = 3.8 V peak-to-peak)

Fig. 42(b).



$$I_2 = \frac{V_{R1}}{R_1} = \frac{1.5/2}{35} = .0215 \text{ ampere (peak)}$$

5 V/cm, 3 mm peak-to-peak

Fig. 42(c).

EXPERIMENT No. 3 (con't.)

NOTE: At this point it is noted that sensitivity of circuit has been reduced. In other words, it is difficult to obtain "on" and "off" switching with only a 0.4-volt deviation in V_2 (load voltage).

<u>Calculations</u>:

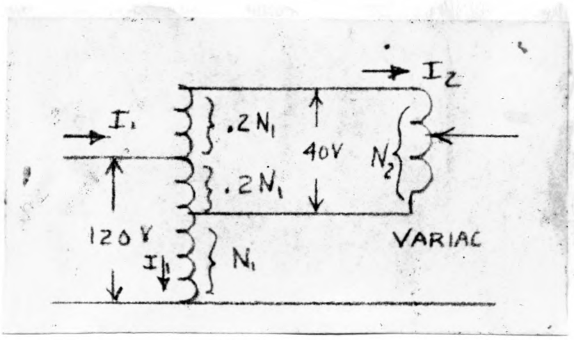


Fig. 43.

Exciting ampere-turns necessary to excite autotransformer at no load is 1.2 $N_1 I_{ex}$. Exciting NI required for variac = $I_2 N_2$. Summing NI available for the autotransformer gives results as shown below.

$$-.2\, N_1 I_2 + .2\, N_1 (I_1 - I_2) + I_1 N_1 = 1.2\, N_1 I_{ex}$$

$$1.2\, I_1 - 0.4\, I_2 = 1.2\, I_{ex}$$

$$I_1 = \frac{1.2\, I_{ex} + 0.4\, I_2}{1.2}$$

$$I_1 = I_{ex} + 0.333\, I_2$$

Both I_{ex} and I_2 will be small. The autotransformer requires a low exciting current (I_{ex}). I_2 is small since the variac is now operating at reduced voltage of 40 volts.

I_1 tested only 10.87 ma at the factory. Finer adjustment is available on output voltage as well.

EXPERIMENT No. 4

Purpose: To determine the sensitivity of the control circuit and test new schemes for improving sensitivity.

Procedure:

I A. Calculate and test the effect of adding a control winding in series with the one now in use for each magnetic amplifier.

B. Calculate and test the effect of eliminating the tap-down "amp adjust" potentiometer of the sensing circuit while at the same time reducing the tap-down resistor of the reference circuit.

II A. Check out the circuit on ±1, ±2, and ±3-volt band width. Check effect of increased bias upon feedback. Picture bias current on scope.

B. Test control with smoothing choke in bias circuit in lead 36. Determine values of bias resistors needed at various band widths.

C. Test circuit for operation with respect to snap action, sensitivity, feedback resistance, relay and timer operation.

Data: 7-8-60

I A. Information will be generalized as follows. With only one set of control windings in use (as in the original circuit), sensitivity is found to be worse than with the original filter arrangements. Somewhere between 80,000 and 83,000 ohms are necessary as feedback resistance to obtain good snap action.

EXPERIMENT No. 4 (con't.)

R_f	Band width	Volts above reference		Deviation
80,000	± 1	1.2 "on"	0.45 "off"	0.75
83,000	± 1	1.2 "on"	-0.2 "off"	1.4

The above value of deviation volts between "on" and "off" switching is not permissible.

Next, two sets of control windings were connected in series with results below.

R_f	Band width	Volts above reference		Deviation
80,000	± 1	1.2 "on"	0.7 "off"	0.5
83,000	± 1	1.2 "on"	0.55 "off"	0.65

I B and IIA

Calculations which follow show sensitivity will be improved by eliminating 1800-ohm tap-down resistor (on reference bleeder) and doing away with the "amp adjust" tap-down resistor. Balance circuit with the T_1 variac. This change results in an entirely different effect upon feedback in the ± 1 band width setting from the effect upon the ± 3-volt setting. This appears to be due to the necessary increase in pulsating bias current with the new improved sensitivity. This condition would require a different feedback resistance for each band width setting, which is out of the question.

Date: 7-14-60

II B. With the "amp adjust" tap-down resistor eliminated, and only 420 ohms tapped down on the reference bleeder, the bias circuit was modified. A 1.4-henry choke filter at point 36 is satisfactory. A bias transformer with a

EXPERIMENT No. 4 (con't.)

12.6-volt secondary is now used.

Values of needed bias resistors are given below:

Band width setting	Resistor number	Ohms
±3	R_7	149.7
±2	R_8	273.5
±1	R_9	477.9
±3	R_{10}	165.7
±2	R_{11}	288.8
±1	R_{12}	488.3

II C. Comments

Results are very good. A value of 0.4 volt gives good "on-off" tripping for timer. About 0.65 volt needed for "on-off" relay operation. See Experiment 5 for more details.

Calculations:

Calculations for improving sensitivity of the control circuit. The sensing and reference circuits are reduced and simplified by means of Thevenin's theorem.

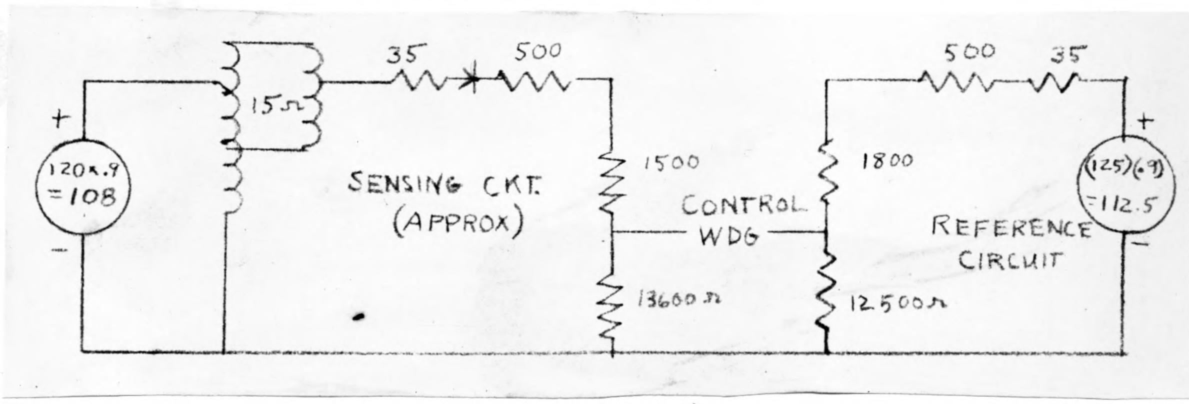


Fig. 44(a).

EXPERIMENT No. 4 (con't.)

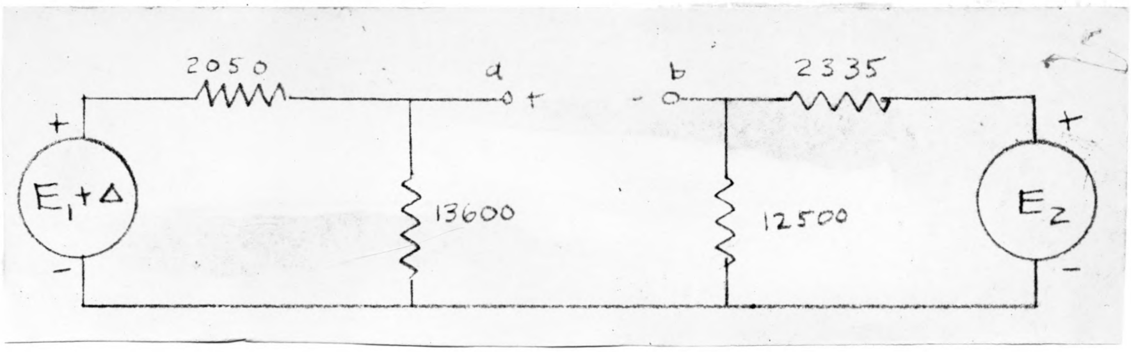


Fig. 44(b).

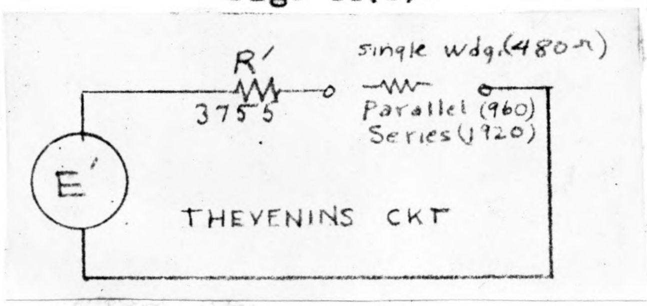


Fig. 44(c).

$$E' = E_{ba} = E_{oa} - E_{ob}$$

$$= (E_1 + \Delta)\frac{13600}{13600 + 2050} - E_2 \frac{12500}{12500 + 2335}$$

$$= \Delta \frac{13600}{13600 + 2050} + \left(E_1 \frac{13600}{13600 + 2050} - E_2 \frac{12500}{12500 + 2335}\right)^*$$

$$= \Delta \frac{13600}{15650} = 0.868\ \Delta$$

*Balance to zero. Δ is the deviation volts.

$$R' = \frac{2050 \times 13600}{2050 + 13600} + \frac{2335 \times 12500}{2335 + 12500} = 3755 \text{ ohms}$$

$$I_{control} = \frac{E'}{R' + R_{winding}} = \frac{0.868}{3755 + 960_{single\ winding}} = 0.184\ \Delta \text{ ma}$$

Available control current for 0.4 volt (a-c) deviation:

I = 0.184 x 0.4 x 0.9 = 0.0662 ma
reduction factor of choke input filter

EXPERIMENT No. 4 (Con't.)

Table 2. Sensitivity comparison.

Remarks	I variation in 0.4 volt a-c (ma)	Relative sensitivity based on (1)
(1) First circuit used after going to choke input filter (single control winding)	0.0662	100%
(2) Replace 1800-ohm from reference tap-down with 380-ohm. Short 2500-ohm "amp adjust", (single control winding)	0.147	222%
(3) Same as (2), but two windings in parallel	0.184	278%
(4) Same as (2), but two windings in series	0.104 x 2* = 0.208	314% (used this)
(5) Same as (4), but better chokes (220-ohm instead of 500)	0.235	355% (Possibles)
(6) Same as (5), but no tap down on reference. (Balance with T_1 variac.)	0.29	437% (Possibles)
(7) Original circuit** using capacitor input filter and single winding	0.203	307% (Possibles)
(8) Same as (7) but two windings in series	0.301	455% (Possibles)

*Factor of 2 due to double turns.

**Original circuit chokes with only 85 ohms resistance. Also Δ is increased by factor of $\sqrt{2}$ due to choke input.

EXPERIMENT No. 5

Purpose: To study the nature of the magnetic amplifier load circuit in use with the "original" load circuit.

Procedure:

I A. Take data for determining the impedance of the timer and

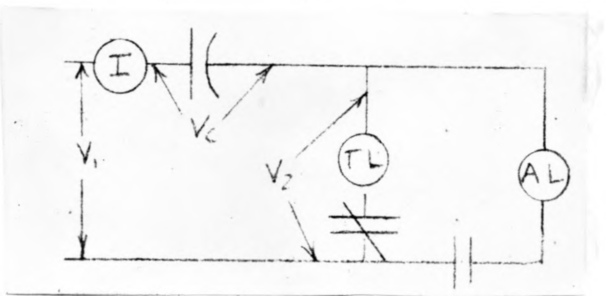


Fig. 45.

relay under operating conditions. Run the sensing voltage of the control circuit up just high enough to trip the "lower" magnetic amplifier. Measure V_1, V_c, V_2, and I. Next, allow the timer to time out and measure I, V_1, V_c, and V_2 with relay closed.

II A. Obtain the open-circuit saturation curve for the autotransformer T_6 with the magnetic amplifier in series.

B. Determine the angle on exciting current of T_6 with V_o = 95. Record V_1, V_2, V_3, V_R, V_{in}, and I.

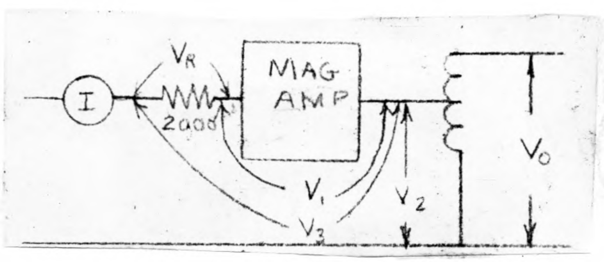


Fig. 46. Circuit for II B.

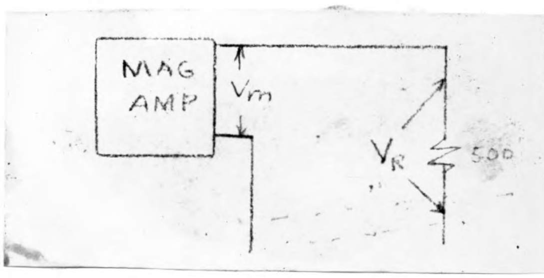


Fig. 47. Circuit for III A.

EXPERIMENT No. 5 (Con't.)

III A. Take data for approximating the impedance of the magnetic amplifier when I = 95 ma.

<u>Data</u>:

I A

V_1	V_C	V_2	I (ma)	Condition
97	105	114	31	Timer running
127	187	116	52	Relay closed

II A

V_o	I_{ex}	V_o	I_{ex}
63	10	105	34
75	13	116	49
87.5	18.5	122.5	61
94	22.5	130	78

II B

V_o	V_1	V_2	V_3	V_R	V_{in}	I (ma)
95	48	42	82	46	119	25

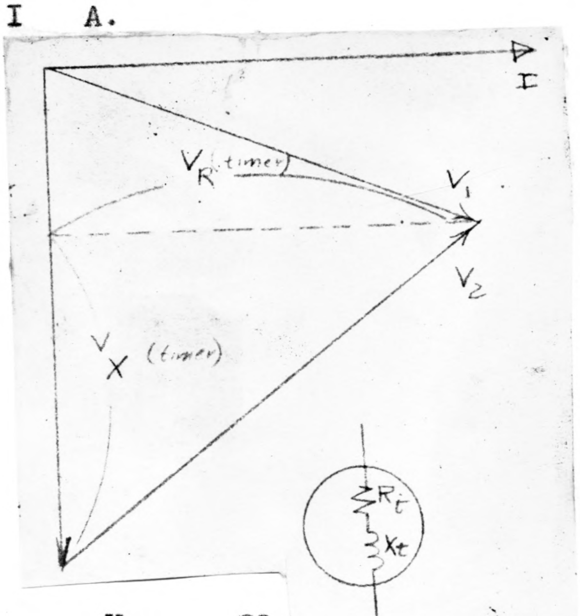
III A

V_R	V_m	V_L	I (ma)
38	85.5	119	95
45	76	119	105

EXPERIMENT No. 5 (Con't.)

Calculations:

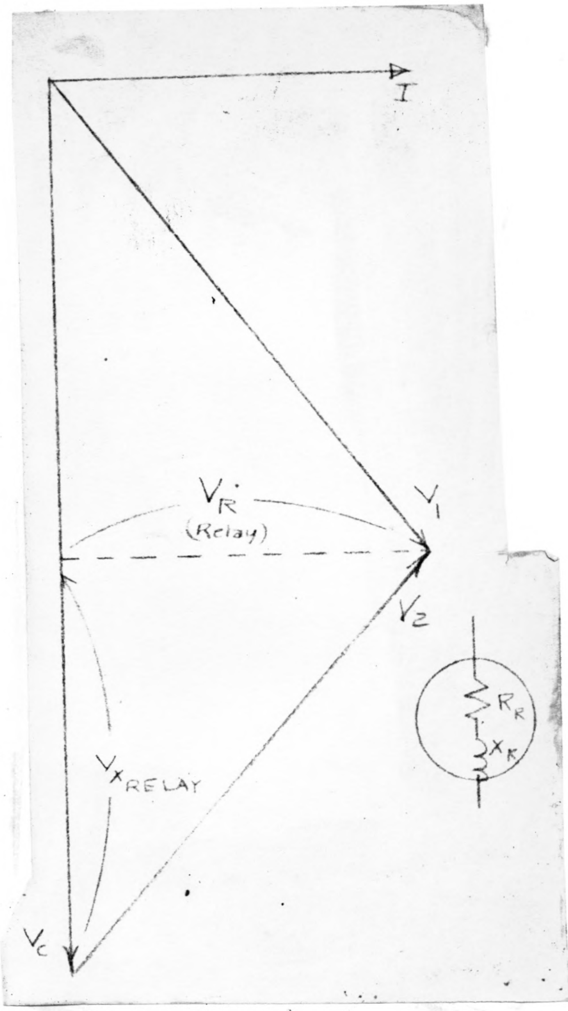
I A.



$$R_t = \frac{V_{R_t}}{I} = \frac{91}{0.031} = 2940 \text{ ohms}$$

$$X_t = \frac{V_{X_t}}{I} = \frac{70}{0.831} = 2260 \text{ ohms}$$

Fig. 48(a). Vector diagram (timer).



$$R_R = \frac{V_{R_R}}{I} = \frac{76.5}{0.052} = 1460 \text{ ohms}$$

$$X_R = \frac{V_{X_R}}{I} = \frac{86.7}{0.052} = 1670 \text{ ohms}$$

Fig. 48(b). Vector diagram (relay).

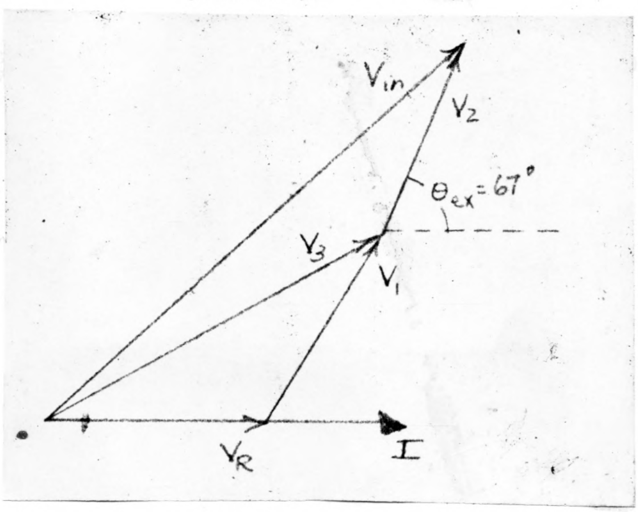


Fig. 49. Vector diagram for II-B.

EXPERIMENT No. 5 (Con't.)

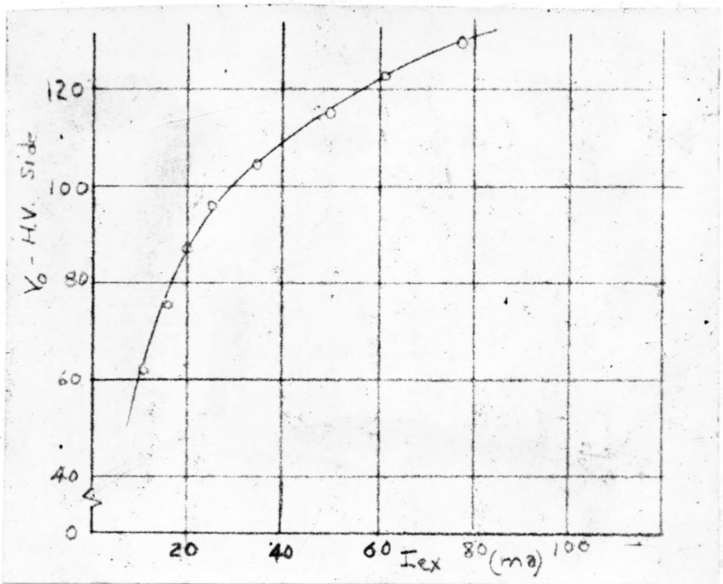
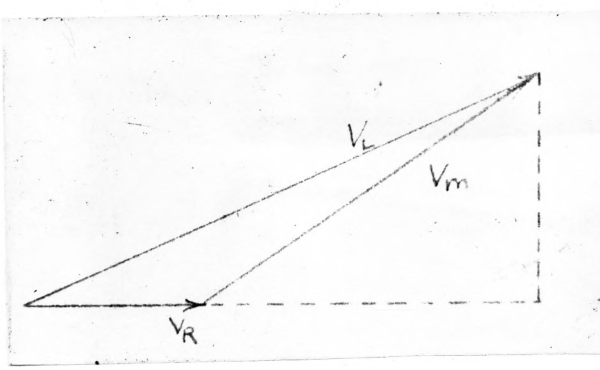


Fig. 50. II-A. O.c. saturation curve for T_6.

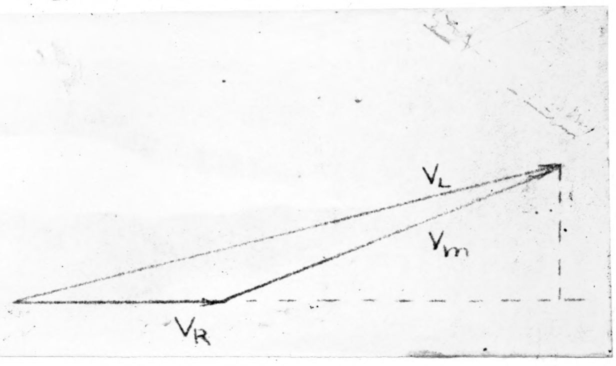
III A. Vector diagrams for approximating magnetic amplifier impedance at a given voltage (V_R).



$R_m = 758$

$X_m = 495$

Fig. 51(a).



$$R_m = \frac{V_{mR}}{I} = \frac{72}{0.105} = 686$$

$X_m = 124$

Fig. 51(b)

EXPERIMENT No. 6

Purpose: To study methods for "trimming up" the load circuit of the magnetic amplifier to assure proper operation of timer and relay.

Procedure:

I A. Replace the selenium rectifiers with silicon diodes in the magnetic amplifier circuit. If satisfactory, make this a permanent change in the circuit.

II A. Test the effect of adding 3500 ohms in series with the lower timer. Note effect upon feedback resistance method. Allow timer to time out and compare feedback needed with relay to that needed with timer.

II B. Determine by calculation the necessary changes for matching the clock and relay circuit (both with and without 3500 ohms in series with the timer).

III Remove C_5 and C_6. Calculate the necessary capacitance across 17 - 58 and 17 - 51 for minimizing magnetic amplifier current. Place this value in the circuit and check operation of timer and relay together. Note any tendency of relay to hunt, necessary feedback resistance, sensitivity, etc.

IV Test a 90-volt relay coil to determine whether it would prove superior to the 115-volt coil.

Data: Date 6-28-60

I Silicon diodes check OK, and comparable to selenium with respect to feed back resistance necessary.

EXPERIMENT No. 6 (Con't.)

II A

	R_{13}	V_{in}	V_c	V_R	V_T	V_A	I(ma)
(1)	76K	97	105	0	114	114	31
(2)	86K	126	64	61	74	126	18.5

Remarks: (1) $R_s = 0$. Timer fails at times to stop when magnetic amplifier trips "off". Timer voltage must drop below 12 volts. Refer to Fig. 52.

(2) $R_s = 3500$. Note the increased value of R_{13}. Sensitivity OK but lower current changes feedback characteristics. Relay and timer are ill-matched.

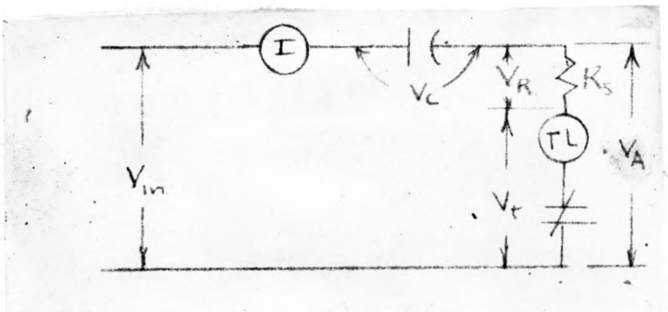


Fig. 52.

II B. See calculation which follows. Test indicates two faults. Hunting of relay and if 3500 ohms are used with timer, timer voltage is low. Circuit when matched as per calculation works well with respect to feedback, however.

III See calculation. Data of <u>7-18-60</u>.

EXPERIMENT No. 6 (Con't.)

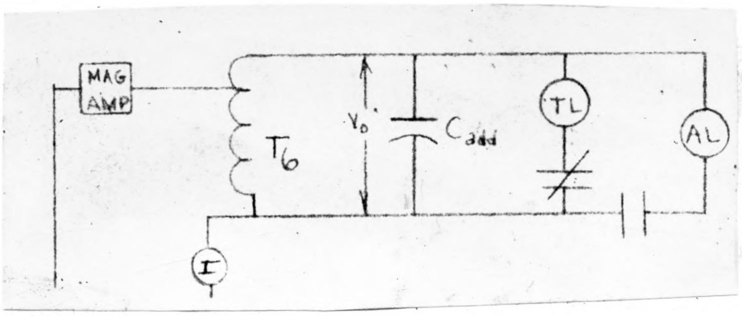


Fig. 53.

Table 3. Data for Experiment 6, Part III.

R_f	C_{add}	I(ma)	V_o	Remarks
Timer running				
76K	0	92	82	
76K	1 mfd	89	95	
76K	1.25 mfd	96	100	
76K	1.5 mfd	104.5	105	Sensitivity good
76K	2 mfd	122	110	
Relay closed				
76K	1.5 mfd	99	95	Hunting eliminated*;
76K	2.0 mfd			works well

*Sensitivity also good. Good definite snap action for magnetic amplifier.

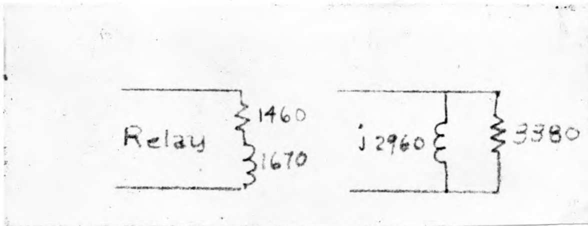
Calculations:

II B. Calculations for matching timer with relay. First the series representation of each is converted to a parallel equivalent. Then match.

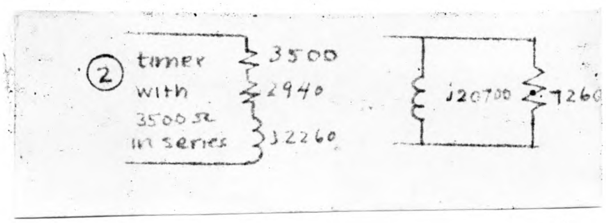
$$Y_p = \frac{1}{Z_s} = \frac{1}{R_s + jX_s} \cdot \frac{R_s - jX_s}{R_s - jX_s} = \frac{R_s}{R_s^2 + X_s^2} - \frac{jX_s}{R_s^2 + X_s^2} = G - jB$$

$$R_p = \frac{1}{G} \; ; \; X_p = -\frac{1}{B} \; ; \; R_p = \frac{R_s^2 + X_s^2}{R_s} \; ; \; X_p = \frac{R_s^2 + X_s^2}{X_s}$$

$$R_p = \frac{(2940)^2 + (2260)^2}{2940} = 4670 \qquad X_p = \frac{(2940)^2 + (2260)^2}{2260} = 6080$$

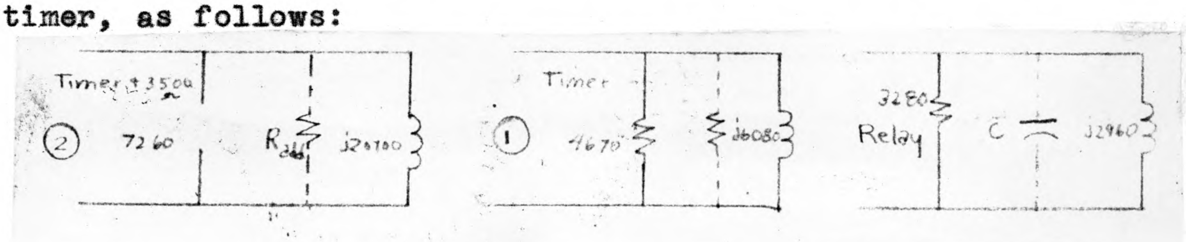


$$R_p = \frac{(1460)^2 + (1670)^2}{1460} = 3380; \quad X_p = \frac{(1460)^2 + (1670)^2}{1670} = 2960$$



$$R_p = \frac{(6440)^2 + (2260)^2}{6440} = 7260; \quad X_p = \frac{(6440)^2 + (2260)^2}{2260} = 20700$$

In order to match timer impedance with relay, add capacitance in parallel with relay, and resistance in parallel with timer, as follows:



$$\frac{7260 \times R_{add}}{7260 + R_{add}} = 3380$$

$$(7260 - 3380)R_{add} = 3380 \times 7260$$

$$R_{add} = 6330$$

EXPERIMENT No. 6 (Con't.)

$$\frac{4670 \times R_{add}}{4670 + R_{add}} = 3380$$

$$(4670 - 3380)R_{add} = 3380 \times 4670$$

$$R_{add} = 12300$$

Match circuit with (1)

$$\frac{2960 \cdot X_{add}}{2960 + X_{add}} = 6080$$

$$X_{add} = -5760$$

$$C_{add} = 0.46\ \mu f$$

Match circuit with (2)

$$\frac{2960 \cdot X_{add}}{2960 + X_{add}} = 20700$$

$$X_{add} = -3450$$

$$C_{add} = \frac{1}{2\pi f X} = 0.77\ \mu f$$

III Approximate calculations for reducing magnetic amplifier current to a minimum, thereby reducing IZ drop at magnetic amplifier when in "tripped" condition. Refer all impedances to the low-voltage side of T_6 (2.2 turns ratio).

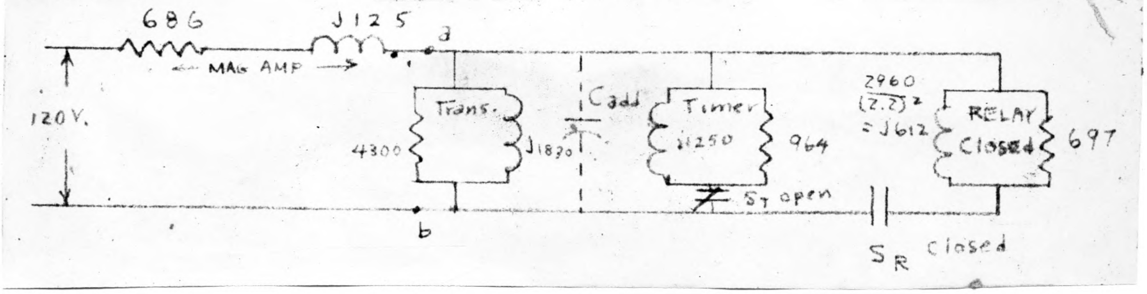


Fig. 54.

EXPERIMENT No. 6 (Con't.)

In order to set up parallel resonance at the right of a-b, add C in parallel as shown in Fig. 54.

$$\left| X_c \right| = \frac{X_{tr} X_{relay}}{X_{tr} + X_{relay}} = \frac{1830 \times 612}{1830 + 612} = 458 \text{ ohms}$$

$$C_{add} = \frac{1}{2\pi f X_c} = 5.79 \mu f$$

$$\text{Based on L.C., } C = \frac{5.79 \mu f}{(2.2)^2} = 1.2 \mu f$$

Note: Any capacitance above this value will have the effect of increasing magnetic amplifier current. Any change in current will alter the magnetic amplifier reactance.

Upon opening, relay reactance drops, circuit to the right of a-b becomes inductive, V_{a-b} will drop further, thus reducing hunting.

EXPERIMENT No. 7

<u>Purpose</u>: To determine the accuracy of the line drop compensator.

<u>Conditions</u>: Use the original LDC in connection with the test circuit as shown in Fig. 55.

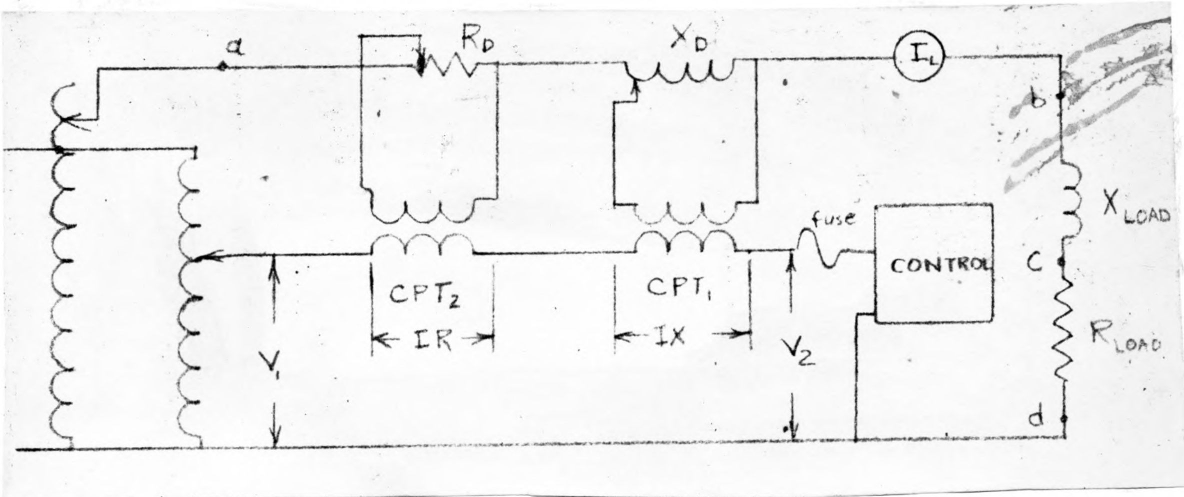


Fig. 55.

<u>Procedure</u>:

1. With I_L at approximately 0.8 power factor, take data at X_D = 0, with dial (R_D) variable from 0 to 24. Record IR, IX, IZ, I_L, V_{cd}, V_{ac}, V_{ad}, V_1 and V_2. Hold V_2 constant at 120 volts.

2. Repeat (1) for R_D = 0 and X_D variable from 0 to 24.

3. Repeat (1) for $R_D = X_D$ where both dials vary from 0 to 24.

4. Repeat Parts 1, 2, and 3 at approximately unity power (referring to circuit a-d).

5. For V_2 = 120 volts, calculate what V_1 should read and plot comparison curves.

Table 4. Data for Experiment 7.

Dial R	Dial X	I_L	V_1	V_2	IR	IX	IZ	V_{cd}	V_{ac}	V_{ad}
Date:	8-5-60									
0	0	5	120.5	120			0.4	89	71.0	118
4	0	5	123.6	120	3.2	0	3.6	88	71.0	118
8	0	5	126.6	120	7.6	0	7.6	88	71.0	118
12	0	5	130.0	120	12.2	0	12.2	88	71.0	119
16	0	5	134.0	120	16.4	0	16.5	88	71.0	119
20	0	5	138.0	120	21.0	0	21.2	88.6	72.0	121.5
*24	0	5	141.0	120	24.5	0	24.8	88.4	72.0	121.5
0	4	5	123.8	120	0	3.8	3.9	87.5	70.5	116.5
0	8	5	127.0	120	0	9.4	9.4	88.0	71.4	118.2
0	12	5	129.2	120	0	14.0	14.0	88.4	71.0	118.0
0	16	5	132.3	120	0	18.6	18.5	88.5	71.0	117.6
0	20	5	135.0	120	0	22.6	22.6	88.0	71.0	117.6
0	24	5	137.5	120	0	26.8	26.5	89.0	71.2	118.0
4	4	5	126.8	120	3.0	4	6.4	88.0	71.0	118.0
8	8	5	133.0	120	7.4	9.5	13.0	89.0	71.5	119.0
12	12	5	140.0	120	12.0	14.0	20.0	88.0	71.4	119.5
16	16	5	146.5	120	16.2	18.4	27.0	88.0	71.0	119.5
20	20	5	153.0	120	20.4	22.2	33.6	87.5	70.2	119.4
*24	24	5	161.0	120	25.0	27.0	40.8	88.0	71.5	121.0

*NOTE: Removing fuse increases V_2 by 0.5 volt when Dial R = 24.
Removing fuse increases V_2 by 0.5 volt when Dial X = 24.
Removing fuse increases V_2 by 1.0 volt when Dial R = X = 24.

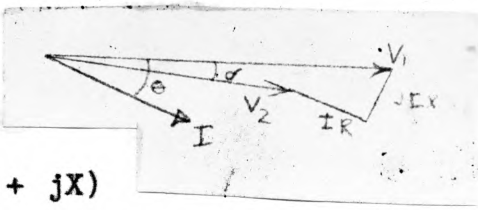
Table 5. Data for Experiment 7.

Dial R	Dial X	I_L	V_1	V_2	IR_D	IX_D	IZ_D	V_{cd}	V_{ac}	V_{ad}
Date:	8-5-60									
8	0	5	128.0	120	7.6	0	7.6	88.2	6.0	91.0
16	0	5	136.5	120	16.5	0	16.5	88.6	7.0	92.5
*24	0	5	145.5	120	25.5	0	25.5	89.0	8.4	95.2
0	8	5	121.6	120	0	9	9	88.0	5.0	89.5
0	16	5	122.0	120	0	17.8	17.8	88.0	5.5	89.5
* 0	24	5	122.0	120	0	26.2	26.2	88.0	5.5	89.5
8	8	5	129.0	120	7.4	8.8	12.8	88.5	6.0	91.4
16	16	5	138.5	120	165.0	18.0	26.8	88.6	7.0	93.0
*24	24	5	147.4	120	25.0	26.5	41.0	89.0	8.2	95.0

*NOTE: Removing fuse raises voltage 0.5 volt when R = 24, X = 0.
Removing fuse raises voltage 0.5 volt when R = 0, X = 24.
Removing fuse raises voltage 1 volt when R = 24, X = 24.

EXPERIMENT No. 7 (Con'd.)

Calculations:



$$V_1 = V_2 \angle\delta + I \angle\theta\,(R + jX)$$

$$= V_2(\cos\delta + j\sin\delta) + IR(\cos\theta + j\sin\theta) + jIX(\cos\theta + j\sin\theta)$$

$$V_1 = (V_2\cos\delta + IR\cos\theta - IX\sin\theta) + j(V_2\sin\delta + I_2 R\sin\theta + I_2 X\cos\theta)$$

(1) Set reals equal; (2) set imaginaries equal

(1) $V_1 = V_2\cos\delta + IR\cos\theta - IX\sin\theta$

(2) $0 = V_2\sin\delta + I R\sin\theta + I X\cos\theta$

From (2) $$\sin\delta = \frac{-I R\sin\theta - I X\cos\theta}{V_2}$$

then $$\cos\delta = \frac{\sqrt{V_2^2 - (-IR\sin\theta - IX\cos\theta)^2}}{V_2}$$

Substituting in (1),

$$V_1 = \frac{V_2}{V_2}\sqrt{V_2^2 - (-IR\sin\theta - IX\cos\theta)^2} - IX\sin\theta + IR\cos\theta$$

Note: For inductive loads, $\sin\theta$ is (-).

Sample calculations for data of 8-5-60:

Dial X = 0; Dial R = 24; $\theta = 36°$; $\cos\theta = 0.809$; $\sin\theta = 0.588$

$$V_1 = \sqrt{V_2^2 - (IR)^2\sin^2\theta - (IX)^2\cos^2\theta + IR\cdot IX\,|\sin\theta|\,|\cos\theta|} + IR\,|\sin\theta| + IX\cos\theta$$

$$= \sqrt{(120)^2 - (24.5)^2(.588)^2 - 0 + 0} + 24.5 \times .809$$

$$= \sqrt{14195} + 19.8 = 119 + 19.8 = 138.8$$

Measured $V_1 = 141.0$. Deviation $= \dfrac{2.2}{138.8} = 1.59\%$

EXPERIMENT No. 7 (Con'd.)

To estimate the magnitude of the error, refer to Fig. 17(b).

$I_1 = 5 \qquad I_{ex} = 0.35$

$$\sin X = \frac{0.35}{5} = 0.07; \quad X = 4.2°; \quad \text{now } \theta = 36° - 4.2° = 31.8°$$

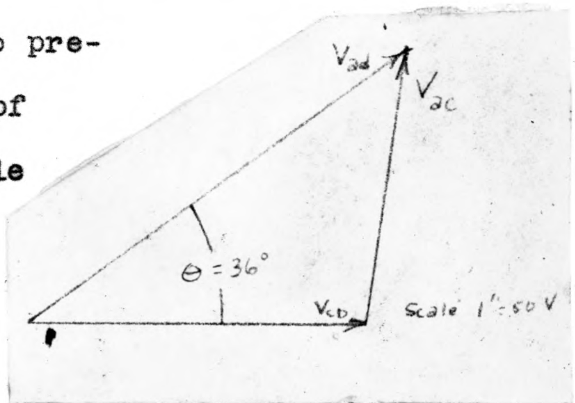
Now calculate V_1 based on 31.8°. Sin θ = 0.527, cos θ = 0.85.

$$V_1 = \sqrt{(120)^2 - (0.527)^2(24.5)^2} + 0.85 \times 24.5$$
$$= \sqrt{14232} + 20.8$$
$$= 119.3 + 20.8 = 140.1$$

Control current is responsible for about 0.5 V.

140.1 + 0.5 = 140.6 $\longrightarrow$ compares with measured value of 141.0

Vector diagram (applying to preceding sample) for determining pf angle. The angle θ is that angle between I and V_1.



R = 0; X = 24 (dial settings). Pf = 0.996, θ = 3.7°.

V_1 = 118.7 (calculated) $\qquad$ V_1 = 122.0 (measured)

Deviation = 3.3 V (0.5 V of which is accounted for by control current)

The remaining 2.8 volts must be accounted for as follows (see Figs. 15(a) and 15(b)).

$P_{ohmic} = I^2 R_{ohmic} = (5)^2(0.0675) = 1.69$ watts

P_{core} = 0.3 watt; 0.30

EXPERIMENT No. 7 (Con'd.)

P_e = 1.99 watts in 26.8 volt-amperes

or V_{R_e} = 1.99 volts in 26.8 volts

accounts for much of deviation.

Data used: R = X = 24 (dial); pf = 0.814; sin θ = 0.58

IR = 25; IX = 27

V_1 (calculated) = 154.5 V_1 (measured) = 161

Deviation = 6.5 volts (maximum error)

One volt is accounted for in drop due to control current (see data). Other errors are due to:

(1) R in X_{var}

(2) Phase shift of IR due to exciting current of CPT_2

(3) V_2 is also shifted in the process (see Fig. 19).

$$V_1 = \overset{(3)}{V_2 \cos \delta} + \overset{(2)}{I_R R \cos(35.5 - 4.2)} + \overset{(1)}{IR_X \cos 35.5°} + IX \sin 35.5°$$

$$= 120 \cos \delta + 25 \cos 31.3° + 2.0 \cos 35.5° + 27 \sin 35.5°$$

$$= 120 \cos \delta + 38.7$$

Summing vertical components on Fig. 19:

$$0 = -25 \sin 21.3° - 2 \sin 35.5° + 27 \cos 35.5° - 120 \sin$$

$$120 \sin \delta = -13 - 1.16 + 22 = 7.8$$

$$\sin \delta = 7.8/120 = 0.065; \quad \delta = 3.72$$

$$V_1 = 120 \cos 3.72 + 38.7 = 158.6$$

Previous V_1 (calc) = 154.5

3.1 volts of the deviation have been accounted for.

Table 6. Results, Experiment 7.

Tabulation sheet recording measured and calculated values of V_1					
R_{dial}	X_{dial}	$V_1(A)$	$V_1(B)$	$V_1(C)$	$V_1(D)$
Pf = 0.809					
8	0	126.0	126.3	126.6	125.6
16	0	132.8	132.4	134.0	131.5
24	0	138.8	138.5	141.0	137.0
0	8	125.2	124.4	127.0	126.0
0	16	129.9	128.7	132.2	131.0
0	24	133.8	132.6	137.5	136.0
8	8	131.4	130.8	133.0	131.4
16	16	143.2	141.7	146.5	143.0
24	24	154.5	152.2	161.0	153.8
			Note improvement here		
Pf = 0.997					
8	0	127.6	128.0	128.0	127.0
16	0	136.5	136.0	136.5	134.0
24	0	145.4	144.0	145.5	141.5
0	8	120.3	120.4	121.6	121.6
0	16	120.2	120.1	122.0	122.0
0	24	118.8	119.4	122.2	122.1
8	8	127.7	128.2	129.0	127.6
16	16	136.1	136.0	138.5	135.8
24	24	143.9	143.2	147.4	143.0

$V_1(A)$ - Calculated from test IZ without modifications.

$V_1(B)$ - Calculated from dial settings.

$V_1(C)$ - Measured without LDC modifications (Experiment 7).

$V_1(D)$ - Measured with LDC modifications (Experiment 8).

EXPERIMENT No. 8

Purpose: To modify the line drop compensator and again determine its accuracy.

Procedure:

1. Determine by calculation the necessary modification to correct the effect of exciting current upon the IR drop.

2. Determine by calculation the necessary modification for allowing the dial settings to equal the actual IZ drops behind the panel.

3. Determine by calculation the necessary modification to correct for the resistance in X_{var}.

4. Modify the LDC by placing an 8-mf capacitance across the secondary of CPT_2 (points 4 and 5). Reduce the turns of CPT_1 secondary and CPT_2 secondary as explained in summary of Part II.

5. Take data for the LDC circuit exactly as described in Experiment No. 7, Parts 1 to 4, with the modifications noted in Part 4 above.

6. Plot comparison curves of V_1 measured and V_1 calculated.

Table 7. Data, Experiment No. 8

Dial R	Dial X	I_L	V_1	V_2	IR_D	IX_D	IZ_D	V_{cd}	V_{ac}	V_{ad}
0	0	5	120.5	120	0	0	0+	89.5	71.5	118.5
4	0	5	123.0	120	2.5	0	2.5			
8	0	5	125.6	120	6.5	0	6.5	89.0	71.5	119.0
12	0	5	129.0	120	10.4	0	10.6			
16	0	5	131.5	120	14.0	0	14.2	89.0	71.5	120.5
20	0	5	134.4	120	17.8	0	18.0			
24	0	5	137.0	120	21.2	0	21.5	88.4	71.5	121.0
0	4	5	123.2	120	0	3.5	3.6			
0	8	5	126.0	120	0	8.2	8.3	89.0	71.0	117.5
0	12	5	128.5	120	0	12.6	12.6			
0	16	5	131.0	120	0	16.8	16.8	89.0	71.5	118.5
0	20	5	133.6	120	0	21.0	21.0			
0	24	5	136.0	120	0	23.8	23.8	88.4	71.4	117.0
4	4	5	125.2	120	2.5	3.6	5.5			
8	8	5	131.4	120	6.0	8.4	11.3	88.5	71.0	118.5
12	12	5	137.0	120	10.0	12.6	17.2			
16	16	5	143.0	120	14.0	17.0	23.0	89.0	71.5	120.0
20	20	5	148.5	120	17.5	20.8	29.0			
24	24	5	153.8	120	21.0	24.0	34.6	88.5	71.4	121.0

LDC data taken with (1) 8 across 4 and 5 points. Date: 8-11-60.
(2) 37 turns removed from CPT_2.
(3) 21 turns removed from CPT_1.

Table 8. Data, Experiment No. 8.

Dial R	Dial X	I_L	V_1	V_2	IR_D	IX_D	IZ_D	V_{cd}	V_{ac}	V_{ad}
Date: 8-11-60										
0	0	5	120.3	120		0				
4	0	5	123.5	120	2.5	0	2.8	89.0	6.0	91.0
8	0	5	127.0	120	6.0	0	6.0			
12	0	5	130.5	120	10.2	0	10.4	88.5	6.5	92.0
16	0	5	134.0	120	13.9	0	14.0			
20	0	5	138.0	120	17.6	0	17.8	88.4	7.5	93.0
24	0	5	141.5	120	21.0	0	21.3	88.8	8.0	94.8
0	4	5	121.2	120	0	3.0	3.0	88.0	5.5	89.0
0	8	5	121.6	120	0	8.0	8.0			
0	12	5	122.1	120	0	12.4	12.4			
0	16	5	122.0	120	0	16.4	16.4			
0	20	5	122.0	120	0	20.0	20.0			
0	24	5	122.1	120	0	23.6	23.6	87.5	5.5	89.8
4	4	5	124.0	120	2.5	3.5	5.0			
8	8	5	127.6	120	6.0	8.0	10.8	89.0	5.8	91.5
12	12	5	132.0	120	10.1	12.2	17.0			
16	16	5	135.8	120	13.5	13.0	22.5	88.0	7.0	92.5
20	20	5	139.5	120	17.3	20.0	28.0			
24	24	5	143.0	120	21.0	23.6	34.2	88.3	8.0	95.0

LDC data taken with (1) 8 across 4 and 5 points.
(2) 37 turns removed from CPT_2.
(3) 21 turns removed from CPT_1.

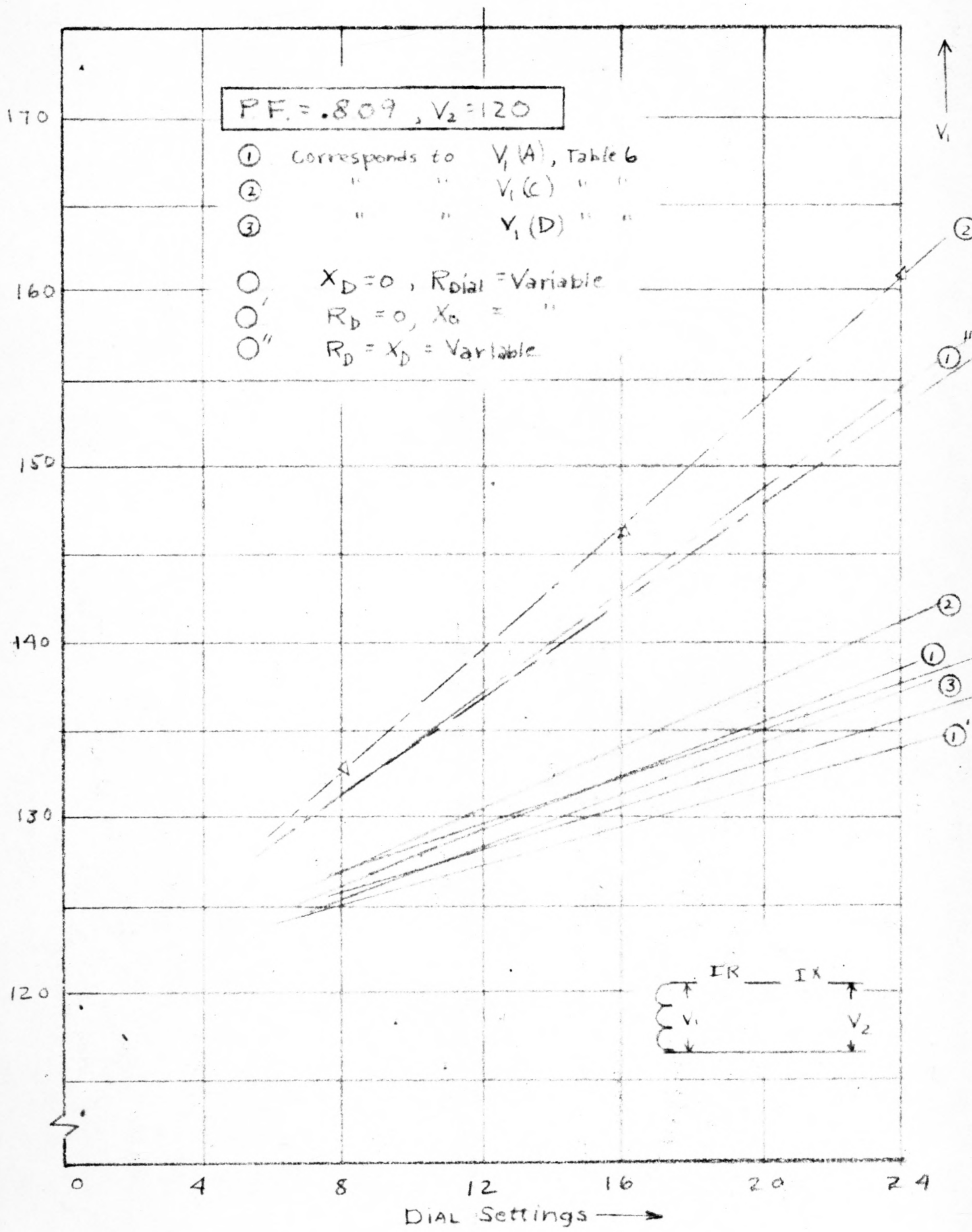

P.F. = .809 , V₂ = 120
① Corresponds to V₁(A), Table 6
② " " V₁(C) " "
③ " " V₁(D) " "
○ X_D = 0 , R_Dial = Variable
○′ R_D = 0, X_D = "
○″ R_D = X_D = Variable
V₁
170
160
150
140
130
120
0
4
8
12
16
20
24
DIAL Settings
IR
IX
V₁
V₂

Fig. 56.

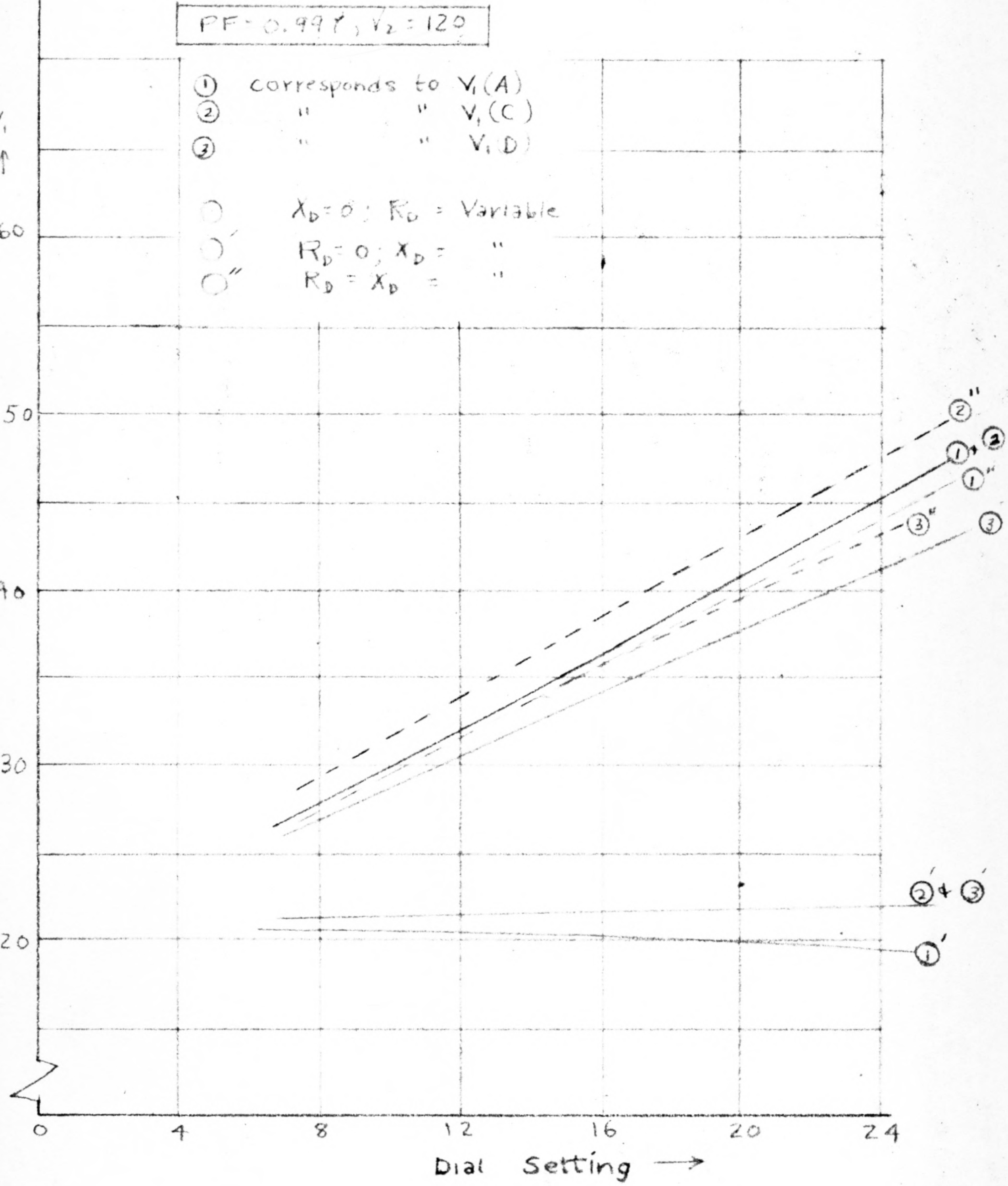

PF = 0.99 ; V_2 = 120
① corresponds to $V_1(A)$
② " " $V_1(C)$
③ " " $V_1(D)$
○ $X_D = 0$; R_D = Variable
○′ $R_D = 0$; X_D = "
○″ $R_D = X_D$ = "
V_1
160
150
140
130
120
0
4
8
12
16
20
24
Dial Setting
②″
① + ②
①″
③″
③
②′ + ③′
①′

Fig. 57.

DEVELOPMENT OF THE LOAD TAP CHANGING TRANSFORMER CONTROL CIRCUIT IN PREPARATION FOR PARALLELING

by

JOHN R. NEUENSWANDER

B. S., University of Kansas, 1954

AN ABSTRACT OF
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It is the purpose of this thesis to record certain developments of the load tap changing (LTC) transformer now in production at the Wagner Electric Corporation. The Wagner LTC control was designed primarily for use with power transformers of above the 1,000-kva range.

The primary function of the control circuit for the LTC is to hold the voltage constant at the "load" point. This "load" point might be defined as the location of the power user, possibly at the end of a transmission line. Since the power might be distributed over a wide area, this point of loading must be clearly specified. The Wagner LTC control circuit under study employs magnetic amplifiers (in place of the voltage regulating relay approach) for initiating a tap change under conditions of under or over voltage.

The developments under consideration in this thesis are primarily those which affect paralleling procedures. In fact, these developments were made in anticipation of paralleling this unit with other like units as well as units manufactured elsewhere. In order for more than one unit to operate satisfactorily in parallel, each control unit should sense the same load voltage. For example, if one unit senses an over voltage at the load and the other unit does not, the first unit will reduce its output accordingly, thereby causing an unequal loading and the existence of heavy circulating currents between transformers.

Factors which could cause inaccurate representation of load voltage in the control circuit were investigated thoroughly. The control circuit is located at the transformer and must therefore have some means for simulating the line voltage drop (IZ) present between transformer and load. This is done with the line drop compensator. The line drop compensator must be as true a representation of line voltage drop as is possible from a practical standpoint.

The thesis is divided into three parts. The first part concerns the improvement of the control circuit itself, in cutting down inaccuracies of load voltage representation and improving the general operation of the circuit with respect to sensitivity, reliability, etc.

In Part II the line drop compensator is studied and revised for the purpose of improving the simulation of the line voltage drop.

Part III is a study of some of the paralleling schemes to be used. The purpose of Part III is to bring together information concerning various paralleling methods. This part of the thesis could serve as a general guide to the engineer who is faced with the job of adapting one or more of the Wagner units for paralleling with others.

With respect to the improvements in the control circuit, circuit changes are summarized at the end of Part I. The line drop compensator of Part II was revised as summarized at the end of Part II. Other proposals are made which could be adopted at a future date should these changes prove feasible from the standpoint of space and economics.

Experimental data, curves, and calculations follow the body of the thesis and are classified as experiments one through eight. Reference to this section is made from time to time in the body of the thesis for the justification of necessary revisions in the circuit under study.