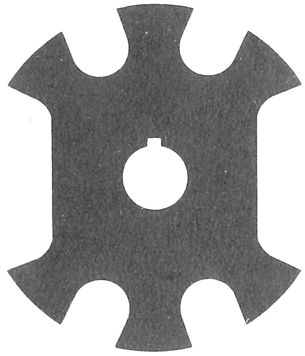
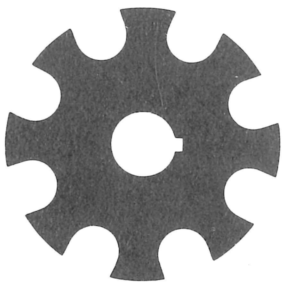
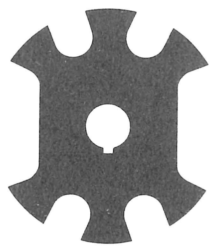


Laboratory Equipment for Demonstrating Electro-Mechanical Forces and Magnetic Circuits





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A REPORT ON NATIONAL SCIENCE FOUNDATION PROJECT NO. 22948
"The development of experimental equipments for showing forces exerted on current carrying conductors in magnetic fields near iron surfaces with different geometries."

CONTENTS

INTRODUCTION

In the modern electrical engineering curriculum, the courses known variously as rotating machinery, alternating-current machinery, electromechanical energy conversion, etc., are being reduced in allotted time or are being considerably modified in content matter. These courses all have in common the study of various geometries of interlinked electric and magnetic circuits. This would include not only machines for electromechanical energy conversion, but also transformers and many other types of electromagnetic devices.

The only place in the electrical engineering curriculum where magnetic circuits are studied is in this particular block of courses. Although commonly considered as being in the field of electric power, this material is not limited to electric power generation and distribution. It also includes a vast host of power utilization and control devices which involve complicated interlinked electric and magnetic circuits. In addition to the usual types of machines frequently studied in undergraduate courses, recent developments have produced various types of electromechanical transducers, magnetic amplifiers, stepping motors, fractional horsepower motors of various sorts, various types of servo and control motors, and many other electromagnetic devices used either alone or in combination with electronics equipment. There is also a considerable trend to combine rectifiers with rotating machines in various special combinations to obtain desired results. Only a relatively few standard types of such equipment can be covered in the usual undergraduate program.

The laboratory study of this equipment is an important part of the electrical engineering curriculum. In such laboratories, students can learn to assemble and use circuits capable of handling not only a few milliamps, but also currents of larger magnitudes. They should also obtain a feel for handling electromagnetic devices of various sorts. The type of instrumentation used may be slightly different than that encountered in the electronic laboratories.

This report covers work supported by NSF Grant 22948 entitled, "The Development of Experimental Equipments for Showing Forces Exerted on Current Carrying Conductors in Magnetic Fields Near Iron Surfaces with Different Geometries." The objective of this project was the development, construction and class testing of prototype models of simple devices to illustrate:

a. Magnetic circuit principles
b. The principles of force on a conductor carrying current in a magnetic field

Most of the commercial machinery and devices available for laboratory study are more or less totally enclosed and the component parts are not available for the student to examine while he is making tests. The device simply becomes another black box which can be tested without obtaining much of a physical picture of what occurs inside the box.

In this particular project we investigated the following types of equipment which are listed below in *increasing* order of complexity and *decreasing* order of success during the project.

a. Single core, single phase laboratory transformer
b. Three core laboratory transformer
c. Torque demonstration equipment
d. Demonstration of forces on a current carrying conductor in a magnetic field

We were able to construct and class test the first three items mentioned above. We have found that class testing is very important in this work. As will be seen from the discussions which follow, there was a tendency for us to be a little bit too ambitious and to incorporate various special features into the prototype models which later class testing showed could not be justified with undergraduate students. In general, with undergraduate students it is desirable to keep things as simple as possible, and while certain special tests and arrangements of equipment are possible, it may not be desirable to use them in regular undergraduate classes, as the students may become confused rather than enlightened.

The above types of equipment as developed in this project will be discussed in detail on the following pages in the order mentioned above.

THE SINGLE CORE SINGLE PHASE TRANSFORMER

One of the objectives of the work on this project was to develop equipment for demonstrating principles of magnetic circuits. We believe that this can be best done by using principles of transformer operation.

The typical transformer experiments usually performed in undergraduate laboratories are rather uninteresting and somewhat unsatisfactory. The student performs the standard short circuit and open circuit tests and computes the constants of an equivalent circuit which somebody tells him applies to the transformer. He may make a load run on the transformer measuring such things as efficiency and voltage regulation. At best, these quantities are rather difficult to measure and of little interest from the student's viewpoint.

A few years ago we attempted to vary this routine in order to give the student a better idea how transformers really operate. We had three single phase, core type transformers in our laboratory, which had half coils on each leg of the core so that we could get at each half coil separately. With this transformer we could demonstrate the difference in equivalent impedance between two coils on the same core leg and coils on opposite legs. The main disadvantage of this particular test was that the connections to the transformer coils were almost impossible for the student to trace out so that a cookbook approach was needed. In an attempt to improve this situ-

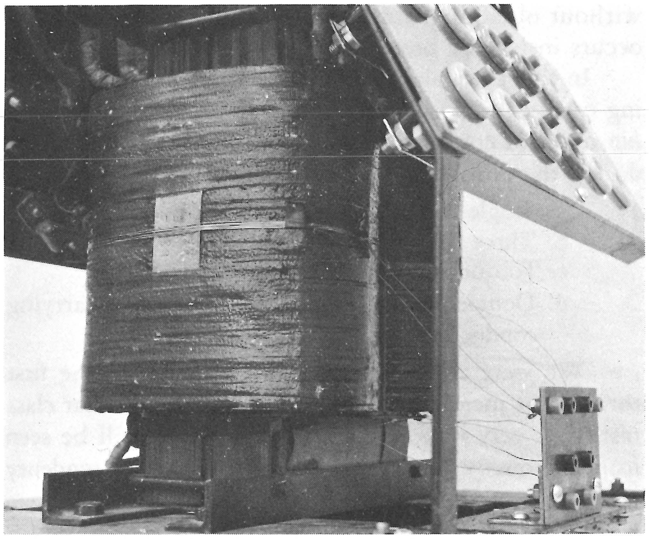


Fig. 1. Single phase core type commercial transformer with search coils added to demonstrate leakage flux.

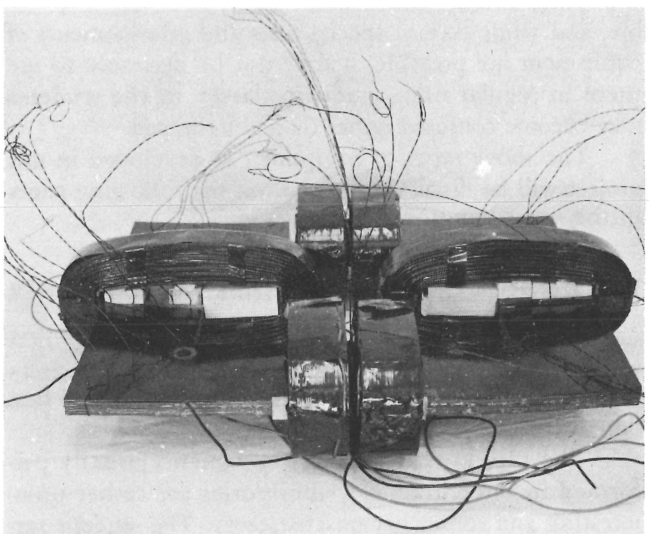


Fig. 2. Core and coil assemby of single core, single phase laboratory transformer.

ation still further, we wound four search coils of ten turns each on these transformers as shown in Figure 1. Two of the coils were wound over the outside of the transformer coils as shown in Figure 1. When the transformer was operated with these two search coils in series opposing, then the difference voltage of the two search coils was proportional to the leakage flux between the two core legs. Undergraduate laboratory experiments could be performed showing the effect of load changes and transformer connections of various sorts on this leakage flux. This was a considerable improvement over the conventional transformer experiment but still left much to be desired.

As part of the work on this project, we constructed a single phase single core laboratory transformer. Figure 2 shows the core and coils of the first prototype unit constructed for this purpose. The laminated iron core

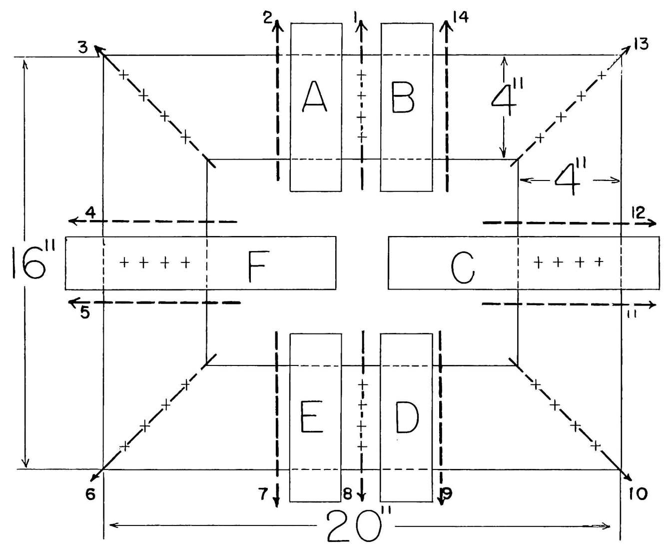


Fig. 3. Iron core dimensions and coil locations for the single phase, single core laboratory transformer, The numbered dash-line arrows show locations of 10 turn search coils.

was made relatively thin and four inches wide with $^1/_{16}$ inch diameter holes drilled at various locations in the core to insert single turn search coils. At each location on the core where single turn search coils were used, four holes were drilled, so that five single turn search coils could be used, with each coil enclosing one-fifth of the cross section area of the iron core at that point of the magnetic circuit. In addition, a number of ten turn search coils were wound completely around the core at different positions around the magnetic circuit.

The diagram of Figure 3 shows the dimensions of the iron core and the locations of the six power coils on the iron core. The crosses indicate the locations of the various $^1/_{16}$ inch diameter holes for the single turn search coils and the dash arrow lines indicate the locations of the various ten turn search coils. Each of the six transformer power coils has the same number of turns and is identified by letter on Figure 3. Table I gives more detailed information for this first prototype single phase laboratory transformer unit.

The core and coils of this transformer unit are mounted in an angle iron framework as shown in Figure 4 and Figure 5. The coil leads of the power coils are brought out on the front of the panel as shown in Figure 5. All search coil leads are brought out to banana jacks on a top panel as shown in Figure 4. The top panel is arranged to simulate the plan view of the magnetic circuit shown in Figure 3. The location of the various jacks on that panel is such that the student knows where the various search coils are located on the iron core with relation to the power coils with merely a glance at the top of the panel. The panel arrangement described proved very flexible and the students had no difficulty whatever in making and understanding the coil connections to both the power coils and the search coils. A group of students is shown in Figure 6 testing this first prototype transformer model.

Table I

Information on Single Phase, Single Core, Laboratory Transformer

Overall Dimensions of Completely Assembled Unit

Height 25-3/4 inches
Width 29 inches
Depth 25-1/4 inches
Estimated weight 150 pounds total

Iron Core

Constructed of L punchings from #29 gage (.014 inches thick) Armco Di-Max M-15 Silicon steel H. R. sheets. Core thickness about 0.706 inches assembled with 46 laminations thick.

Weight of iron core, 39.4 pounds.

Power Coils

There are six power coils of 400 turns each of AWG No. 14 round wire with heavy (double) film thickness of poly-thermaleze insulation.

The four side coils, A, B, D, and E weigh about 7.3 pounds each and have a measured d.c. resistance of 1.334 ohms each at 20°C.

The two end coils, C and F, weigh about 10.3 pounds each and have a measured d.c. resistance of 1.890 ohms each at 20°C.

Class 130 Insulation is used. Coils are each rated at 5.1 amperes, 70°C rise continuous.

Transformer Equivalent Impedances Determined from Short Circuit Tests

Z_{a-b}	=	2.9	+	j	17.18	ohms
Z_{a-c}	=	8.0	+	j	69.4	ohms
Z_{a-d}	=	10.68	+	j	80.4	ohms
Z_{c-f}	=	11.62	+	j	87.0	ohms
Z_{ab-de}	=	6.52	+	j	65.4	ohms
Z_{ad-be}	=	1.62	+	j	7.91	ohms

Note: Z_{a-b} is impedance with coil B short circuited and Coil A excited. A_{ab-de} is impedance with coils D and E short circuited and coils A and B excited and connected in parallel. The same nomenclature applies to the other equivalent impedances.

List of Illustrations and Curves Which Apply To This Transformer

Figure 2. View of Core and Coil assembly
Figure 3. Sketch of core showing dimensions and coil locations
Figure 4. Rear corner view of assembled unit
Figure 5. Front view of assembled unit
Figure 6. Class testing the single phase, single core transformer
Figure 7. No load saturation curve
Figure 8. Leakage flux voltage plotted against secondary load current
Figure 9. Leakage flux voltage plotted against core position

We were able to class test this transformer for about three semesters in our undergraduate laboratories. As was to be expected, our first prototype model had some characteristics which were either undesirable or of no real consequence as far as classroom instruction was concerned. For example, this model had six power coils, each coil having the same number of turns. Our reason for doing this was to be able to study multi-winding transformers. In practice it was found that four coils were entirely sufficient and furnished enough complications for a typical undergraduate student to worry about. However, as a result of using six coils instead of four, the leakage reactance of the coils was greatly increased, as can be shown from the test data in Table I. However, even with the disadvantages mentioned, this equipment was a distinct success from the standpoint of class instruction.

Figure 7 shows the no load saturation curve or magnetization curve taken with only power Coil A excited.

Although many tests are possible with this particular transformer, the following tests proved the most useful and of chief interest to the typical undergraduate student as evidenced from actual classroom experience.

1. The relative amount of leakage flux between coils on the same core leg as compared to that between coils on opposite core legs can easily be determined from short circuit tests. Tests can be made with Coil A as the primary and B as the secondary. Then another test can be made with Coil A as the primary and D or E coil as the secondary, and the results compared. Naturally, the latter tests give the largest value of leakage reactance. In fact, due to the use of six coils and long magnetic circuit, the leakage reactance in the latter case is so large that even with rated voltage on Coil A and with Coil E or D short-circuited, rated current will not circulate in either secondary coil. The arrangement for this particular kind of test is much better than that used for the commercial dry-type transformer shown in Figure 1. No "cook-book" approach is needed as the students can easily trace out the coil connections on the laboratory prototype unit.
2. The closed iron core of the transformer forms one of the simplest of magnetic circuits. The available transformer design information as given in Table I and Figure 3 can be used in combination with the manufacturer's magnetization curve data for the transformer steel used, to compute the RMS value of the transformer exciting current for various 60 cycle voltages

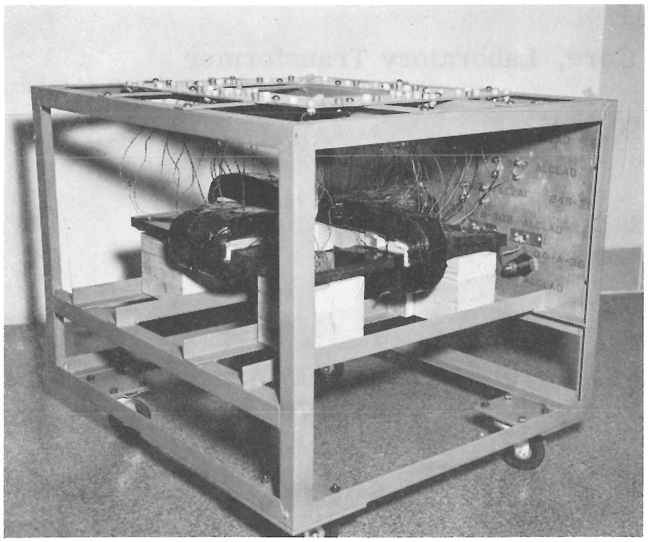


Fig. 4. View of assembled single phase, single core laboratory transformer showing core and coil mounting arrangement.

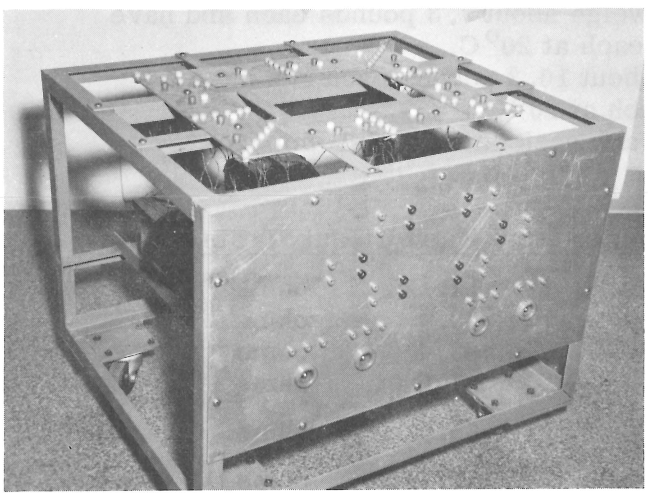


Fig. 5. View of single phase, single core laboratory transformer showing front terminal board for power coil connections, and top terminal board for search coil connections.

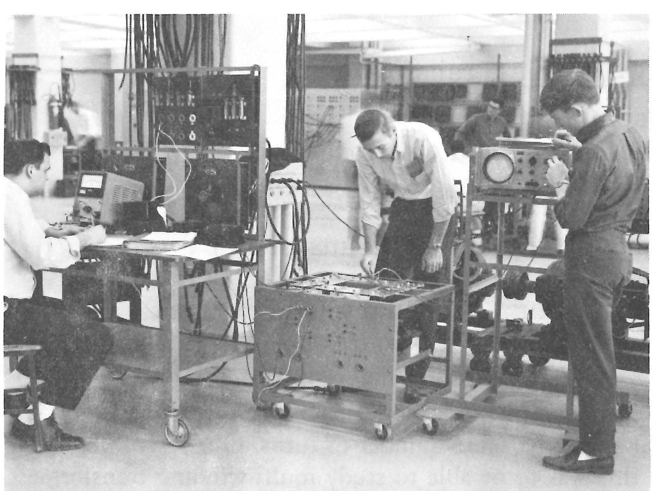


Fig. 6. Class testing the single phase, single core laboratory transformer.

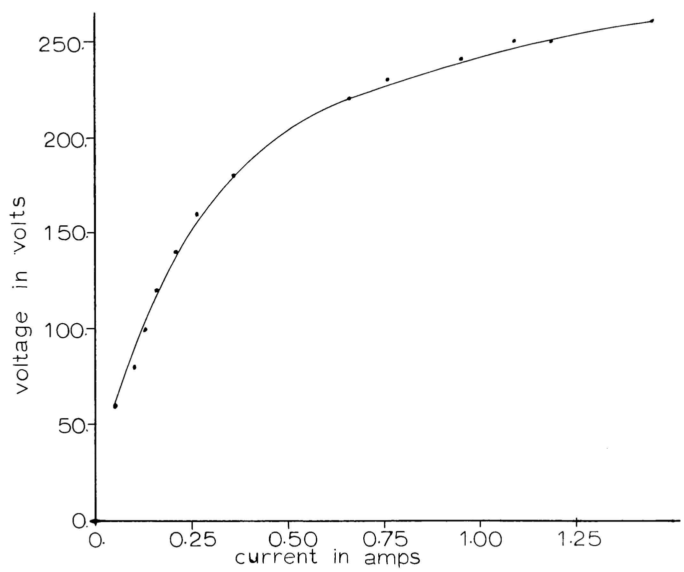


Fig. 7. No load saturation curve for the single core, single phase laboratory transformer. Only power coil A is excited with 60 cycles a-c.

applied to one or more of the transformer coils. To obtain a good check of computation with test quantities, it is desirable to use the actual number of transformer laminations in the computations instead of using the measured thickness of the iron core in conjunction with some assumed stacking factor.

3. The cross section of the iron core is divided into five equal areas by each set of single turn search coils. A vacuum tube voltmeter can be used to show the distribution of flux over the cross section area of the iron core at different parts of the magnetic circuit. In this manner, the relative uniformity of flux density across the iron cross-section in between corners and the bunching up of flux at the inside corners of the magnetic circuit can easily be observed directly by the students. An average voltage reading vacuum tube voltmeter is, of course, best for this work, since the voltage readings are then directly proportional to the flux linked by the single turn search coils. The following test readings illustrate the type of information obtained from such tests. In these tests, 220 volts, single phase, 60 cycles, were applied across power coils A and B in parallel. All other transformer coils were open.

Location of search coil group (See Fig. 3)	VOLTAGES READ WITH - VTVM Between Coils A And B	At Corner Location 6	Between Coils E And D
Position of Core area enclosed by the single turn search coil			
Inside 20%	0.114	0.150	0.091
Next 20%	0.110	0.130	0.094
Middle 20%	0.109	0.110	0.095
Next 20%	0.111	0.076	0.094
Outside 20%	0.110	0.023	0.092
Total reading with all five search coils in series	0.550	0.489	0.465

4. The various single turn search coil voltages can be observed very easily by means of a cathode ray osilloscope. The change of voltage wave shape as one goes around the magnetic circuit can easily be observed. The voltage wave shapes of one or more single turn search coils in series can easily be seen on the oscilloscope. The typical undergraduate electrical engineering student gets considerable enlightenment when he observes five badly distorted non-sinusoidal voltage wave forms add up to give a single sinusoidal voltage wave form and sees how this pattern changes as one goes around the magnetic circuit for various coil combinations.

5. Each ten-turn search coil completely surrounds the iron core and will give vacuum tube voltmeter readings proportional to the total flux enclosed by the coil at its particular location on the core. The use of a ten-turn search coil has the advantage that larger voltages are available for use with the vacuum tube voltmeter. If two of the ten-turn search coils are connected in series so that their voltages oppose each other, the resulting voltage reading will be proportional to the vector voltage difference between the two coils and will be proportional to the leakage flux between them. One test which was used, was to connect power coils A and B in parallel as the primary of the transformer, and load coils E and D as a secondary of the transformer with a resistance load. Ten-turn search coils Nos. 1 and 8 were then connected in series opposing so that a vacuum tube voltmeter connected across these two search coils in series gave readings proportional to the leakage flux between those particular points on the magnetic circuit. A reference to Figure 3 will make it clear where the various coils are located. Figure 8 taken from an undergraduate laboratory report shows the results of such a test. The leakage flux voltage is really the difference voltage between ten-turn search coils 1 and 8, and one can see that the leakage flux increases as the secondary load increases. It will be noted that there is even some leakage flux at no load. This is because of the fact that constructing this prototype transformer with six coils instead of four, with two of the coils being on the ends of the core, considerably spread out the magnetic circuit so that the leakage flux is rather high. Also, the iron cross-section is relatively low for the amount of flux demanded by the primary voltage applied.

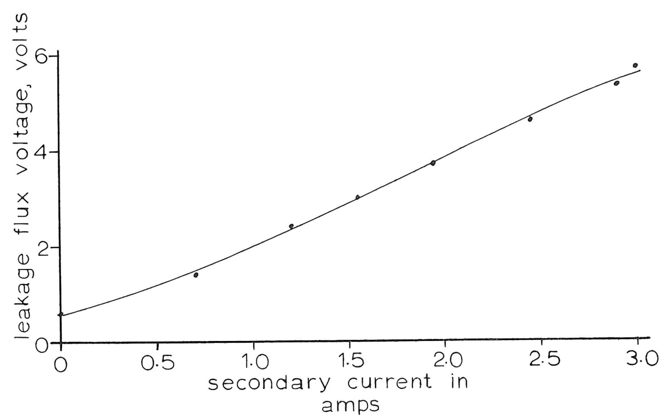


Fig. 8. Leakage flux voltage plotted against secondary load current. A and B are primary coils connected in parallel across 220 volts, 60 cycles.

6. Another possible test using the ten-turn search coil is to use one coil, say number 1 as a reference, and to measure the difference voltage between coil 1 and coil 2, then the voltage between coil 1 and coil 3, and so on, all the way around the magnetic circuit for different conditions of loading. The results of such tests will be somewhat similar to those shown in Figure 9 which was taken from an undergraduate laboratory report. In Figure 9A, coil A is the primary coil, and coil B is short circuited. The ordinate in each case is the difference voltage between coil 1 right beside power coil A and the coil position indicated on the abscissa. At position 6, for example, the difference in voltage between the ten-turn coils at position 1 and position 6 is 1.3 volts, which voltage is proportional to the leakage flux between those two points on the iron core.

When coil A is used as the primary and coil D

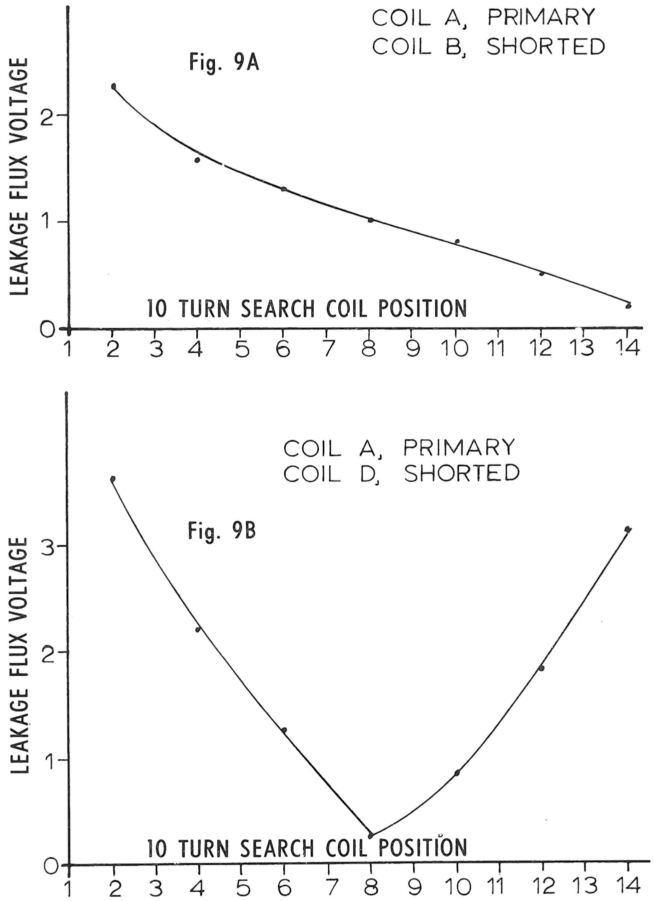


Fig. 9. Leakage flux voltage plotted against position on core during a transformer short circuit test.

on the opposite side of the iron core is short circuited, then the results of Figure 9B were obtained.

This particular type of test was suggested by the group of undergraduate students from whose reports the data of Figure 9 were taken. The data were sufficiently interesting so that we incorporated this particular test in the experiment instructions for other student groups.

The above tests using the prototype single core, single phase laboratory transformer would require two 3-hour laboratory periods for an inexperienced group of undergraduate students or about one and one-half 3-hour laboratory periods for a group of experienced undergraduate students. None of the above tests can be performed on standard commercial transformers built by electrical manufacturers. From the instructional viewpoint, the prototype single phase, single core laboratory transformer was quite successful and the students were much interested in performing practically all of the above tests.

In addition to the above tests there are a few other tests which can be made on this transformer. These include multi-winding transformer tests, the standard open circuit and short circuit tests to determine equivalent circuit constants, load tests for efficiency and voltage regulation, and so on. We did not try to make such tests using the prototype unit as we had plenty of standard transformers available in our laboratory which could be used for making the more routine tests.

Another test possible with the prototype model of the single phase single core transformer is to send direct current through two of the coils, say A and B, or A and D, with the magneto-motive forces opposing each other to simulate the instantaneous value of transformer currents under some phase of transformer operation. The leakage fluxes in the air around the transformer core and coils can then be investigated with a Hall-effect Gaussmeter. The student reaction to this particular test was somewhat mixed. Some student groups thought this test was very worthwhile and quite interesting, whereas others thought that they didn't get very much out of this test for the amount of time involved. There is also the disadvantage that the probe of the Gaussmeter might get tangled up with some of the leads around the iron core. We therefore decided not to incorporate this particular test into our group of standard tests for use on this laboratory type transformer.

THE THREE CORE TRANSFORMER

In addition to the single core, single phase, prototype transformer a three core laboratory prototype transformer was constructed. The principle of construction employed was essentially the same as that for the single core transformer. An iron core 4 inches wide and of relatively shallow depth was used and drilled with $^1/_{16}$ inch diameter holes for single turn search coils as was done for the single core transformer. Each of the three iron cores had four duplicate power coils.

Figure 10 shows the arrangement and identification lettering for the twelve coils of the transformer. The crosses in Figure 10 show the locations of the $^1/_{16}$ inch diameter holes for the single turn search coils and the dash arrows show the location of the ten-turn search coils.

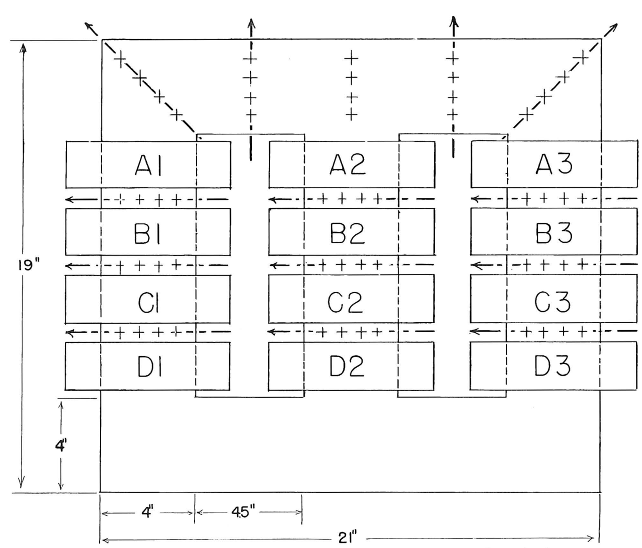


Fig. 10. Core dimensions and arrangement of the core and coils for the three core laboratory transformer. Dash line arrows show locations of 10 turn search coils. Crosses show locations of holes drilled for single-turn search coils.

Figure 11 shows a photograph of the core and coils for the three core transformer on the top where the search coil leads come out. Figure 12 is an assembled view which shows the mounting arrangement for the core and coils in the angle iron frame. Figure 13 shows the top and rear of the assembled three core transformer unit. In this picture, the top panel with the banana jacks used for the search coil terminals is shown. The aluminum panel on which these banana jacks are mounted is of the same plan view and dimensions as the iron core of the transformer. The jacks are located at the approximate locations of the corresponding coils on the core. The relative locations of the twelve power coils are also shown on this top panel.

A front view of this unit is shown in Figure 14. The terminals to the 12 power coils of the transformer are at the top half of the panel. A number of banana jacks and power receptacles are provided on the bottom half of the front panel for external power connections and for making coil cross connections.

Figure 15 shows a laboratory class making tests on the three core laboratory transformer.

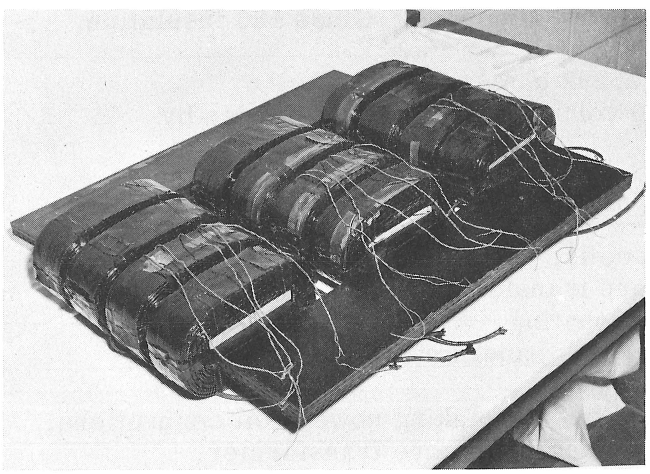


Fig. 11. Core and coils for three core laboratory transformer.

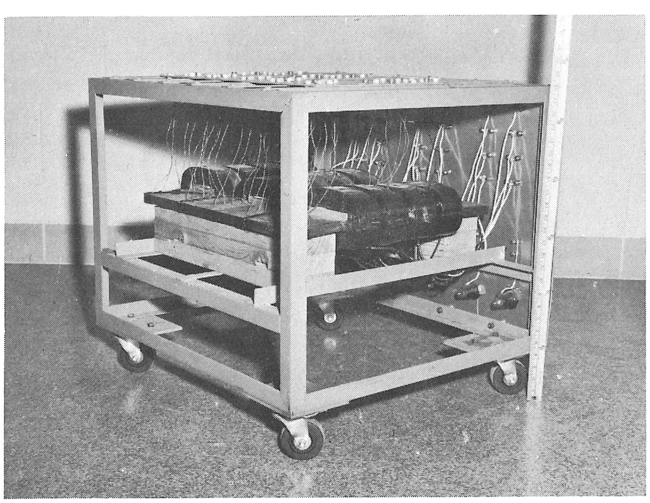


Fig. 12. Three core laboratory transformer assembled. Core and coil mounting arrangement.

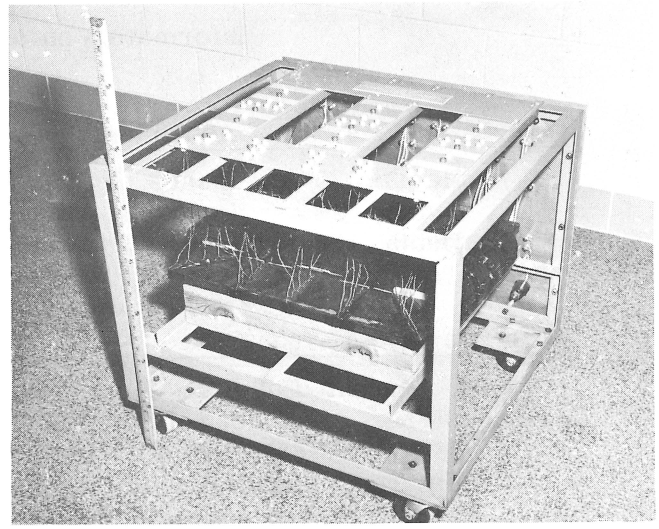


Fig. 13. Top and rear view of the assembled three core laboratory transformer.

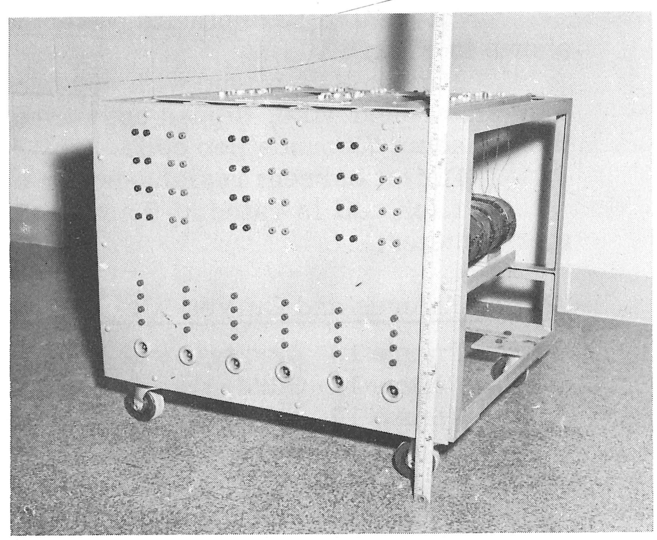


Fig. 14. Front view of assembled three core laboratory transformer.

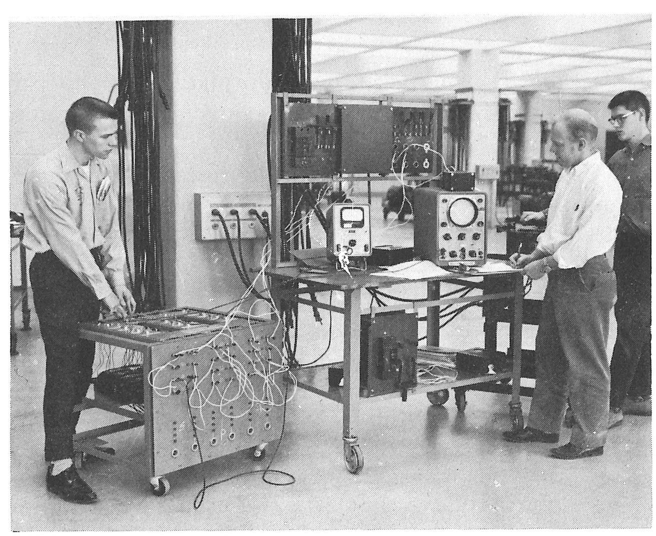


Fig. 15. Class testing the three core laboratory transformer.

Table II
Information on 3 Core Laboratory Transformer

Overall Dimensions of Assembled Unit

Height, 25-3/4 inches
Width, 28 inches
Depth, 26-1/4 inches
Total estimated weight, 205 pounds

Magnetic Circuit-Iron Core

Constructed of E and I laminations from 29 gage (0.014 inches thick). Armco Di-Max M-15 hot rolled silicon steel sheets.
48 laminations thick with an assembled measured thickness of 0.72 inches.
Figure 10 shows the dimensions of the magnetic circuit.
Weight of iron core, 56.8 pounds.

Power Coils

There are 12 duplicate power coils, 4 coils on each core, arranged as shown in Figure 10.
Each coil is wound with 400 turns of No. 14 heavy (double) Poly-thermaleze insulated round wire, dipped and baked in Isonol 31 varnish. Class 130 insulation. Weight about 7 pounds per coil.
Direct current resistance per coil, 1.292 ohms at 20°C.
Each coil is rated at 5 amperes, 230 volts, continuous, 75°C rise by thermometer.

List of Figures and Curves Which Apply To The 3 Core Transformer

Figure 10 Arrangement of core and coils.
Figure 11 Core and coils of the 3 core transformer.
Figure 12 Assembled view showing mounting
Figure 13 Rear top view showing top jack panel for making search coil connections.
Figure 14 Front view showing front panel for making power coil connections.
Figure 15 Student laboratory class testing the 3 core transformer.
Figure 16 Test results obtained with the 3 core unit connected to operate as a saturable reactor.

Table II gives additional information for this particular prototype model of the three core laboratory transformer.

This particular prototype of the three core laboratory transformer was tested in class use for about 3 semesters. The following tests were found to be of the greatest usefulness from the instructional standpoint.

1. *Simple series-parallel magnetic circuit*
With a known 60 cycle voltage applied to an exciting winding, the flux in each core can easily be measured by use of the ten-turn search coils. Using the manufacturer's curves for the magnetic properties of the iron core material, it was relatively easy to check computed values of flux against test values for various systems of excitation. The two most obvious systems to use were of course where the exciting coil was on the No. 1 core giving a simple series-parallel circuit, and the other with the exciting coil on the second or middle core of the magnetic circuit. Other excitation combinations are also possible but these two are the most obvious and useful.

2. *Magnetic core flux transfer*
The phenomena which occur when one or more coils on core No. 1 are energized and various types of loading are employed for the coils on cores 2 and 3 are of considerable interest. For example, if one or more coils on core No. 2 are short circuited, the magnetic flux in this core will transfer to core No. 3. This sort of thing can be investigated in a fair amount of detail. It is quite enlightening to the undergraduate student when he uses a commercial voltmeter to measure the voltage across the open ends of a coil on core

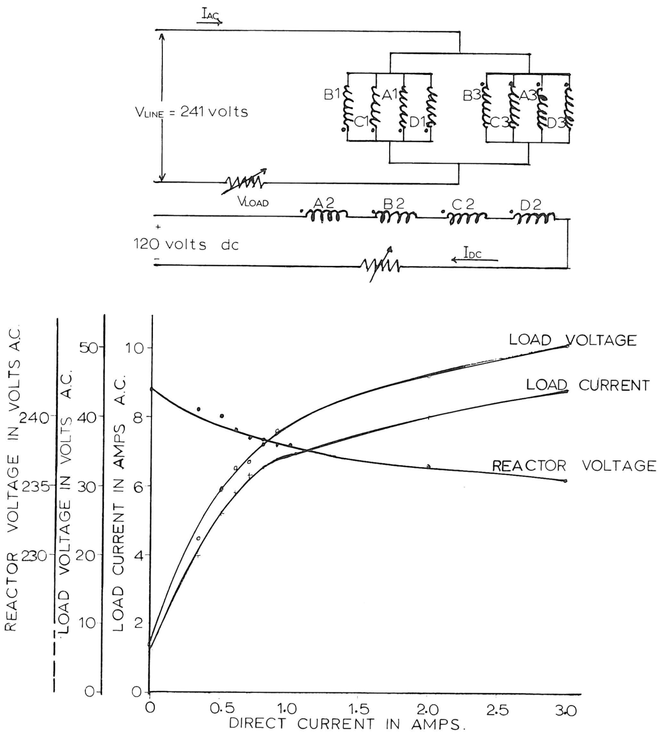


Fig. 16. Saturable reactor circuit and test results using the three core laboratory transformer.

2 and then makes the same measurement with a vacuum tube voltmeter and realizes how sensitive the system is to the impedance of the voltage measuring equipment. It is of considerable instructional value to ask the student to make a number of such test measurements in a qualitative fashion, that is to short-circuit one or more coils on cores 2 or 3 to see what magnitudes of short circuit current and open circuit voltages are obtained with different combinations. The student can then be asked to compute the primary current in the exciting coil on core 1 with either a coil on core 2 or core 3 short circuited using principles of magnetic circuit computations along with what he has discovered from his qualitative tests. All of this is very instructive as regards the fundamental properties of interlinked electric and magnetic circuits.

3. *Three core saturable reactor circuit*
The three core transformer can be connected and tested to demonstrate the principles of saturable reactor operation. For this purpose the four coils on core No. 2, the center leg, are connected in series and used as the d-c control circuit. The four coils on each of the two outer legs are connected in parallel, but arranged so that the M.M.F. of all eight coils will aid each other around the magnetic circuit consisting of cores 1 and 3 in series.

Figure 16 shows the circuit employed and also curves of the test results. It will be noted that a relatively wide range of a-c load voltage and load current can be obtained by varying the direct control current from zero to 1.5 amps. The prototype three core transformer was not designed primarily as a three core saturable reactor so that the results may not be representative of commercial three core reactors, but at least the principles of operation are demonstrated.

The above tests on the three core transformer were found to be the most useful ones which could be performed in our undergraduate laboratory. The following tests were tried out but were considered to be of less value than the tests mentioned above.

1. *Short circuit tests with various coil and core combinations*
There are quite a few combinations which can be tried out. However, an analysis should be made of the most useful combinations to use from the instructional standpoint.
2. *Three phase core type transformer operation*
The three core transformer can easily be used as a three phase core type transformer. We tried using both balanced and unbalanced methods of loading and operation, as well as the standard short circuit tests using various three phase combinations. All of these tests can be made. The only question is how valuable they are in the instruction of undergraduate students. What we found was that the three phase tests took a considerable amount of time on the part of the students, largely on account of the time required to make the power coil connections on the front panel. In the modern electrical engineering undergraduate curriculum not very much time is allotted for a study of polyphase transformer connections. We found it very difficult for the instructors to explain to the undergraduate students just what was happening with some of the connections used. We finally decided that the three phase system of tests would be omitted in the laboratory use of this particular transformer on account of the complexities involved and the time required. Three phase transformer tests can be made, however, using the three core laboratory transformer developed on this project.
3. *Second Harmonic type magnetic amplifier*
The three core prototype transformer can be connected and operated to form a rather crude second harmonic type magnetic amplifier.

With this connection, the four coils on the center leg, core number 2, were connected in series and used as the DC control winding. It was found desirable to insert a choke coil in series with this circuit to prevent a lot of the second harmonic power from leaking back into the DC supply.

Referring to Figure 10 for the coil indentification system Coils B1 and C1 were connected in parallel, and Coils B3 and C3 were connected in parallel, and the two sets of coils were then connected in series in such a way that the second harmonic voltages would add and the fundamental and odd hormonics would oppose each other. The load was then connected across the combination.

For AC excitation, coils A1 and D1 were connected in parallel. These two coils were then connected in series with parallel-connected coils A3 and D3 on core 3 across the 230 volt supply.

The performance of the above combination as a magnetic amplifier was rather poor. The gain was somewhat less than unity. However, the principles of such operation were at least demonstrated. We believe that better results would have been obtained as regards magnetic amplifier operation if a higher exciting voltage had been used or if the coils themselves had been designed for lower operating voltages.

In practice, the magnetic amplifier connection was actually not tested by the students because there was not sufficient laboratory class time available to try it out after the other scheduled tests had been made. Since all of our students will encounter the magnetic amplifier in later courses in control systems we did not attemp to pursue the matter further.

We found that the three core laboratory transformer described above was a welcome addition to our laboratory and was of considerable instructional value. The first group of tests described above, and which were indicated as being the most desirable, could be completed by a typical undergraduate student group in either one or one and a half 3-hour laboratory periods if the group was experienced and in two 3-hour lab periods if the group was relative inexperienced in handling the laboratory equipment.

In general, we felt that the student reaction toward experimental work on both the single core, single phase transformer and the three core transformer was very enthusiastic and very useful from an instructional standpoint. Of course, part of this may have been due to the fact that the equipment was new, the students knew that it had been specially built in our shop, and a few of the students had actually assisted in the construction work. In any event, we felt that the amount of student interest as regards laboratory transformers was very much greater using our prototype models than in performing the conventional tests which had been done in the past using commercial transformers.

CONSTRUCTION OF THE LABORATORY TRANSFORMERS

The two prototype laboratory transformers described were constructed in our Electrical Engineering Department Shop for the most part by student labor under the supervision of our laboratory mechanic. For construction of these transformers it is desirable to have a coil winding machine with a turn counter. It is also necessary to have a shear for shearing the laminations to the desired dimensions.

For the power coils we used Poly-thermaleze insulated wire impregnated in Isonel 31 baking varnish. The insulation system was Class 130 suitable for operation at 130°C. temperature.

Instead of using bolts for the iron laminations, we used adhesive such as is used in the magnetic circuits of small motors. This proved to be very successful and our shop was enthusiastic about the use of the adhesive instead of the bolts after they had become broken in on the procedure used.

In constructing the core and the coils the coils were dipped twice in the insulation varnish and baked twice, the first time for one and a half hours at 300°F. and the second time for 5 hours at 300°F. in an electric oven.

The completed coils were then assembled with the iron core. The adhesive had already been applied to the core laminations and dried. The whole assembly was then placed in the oven and baked for about 8 hours at 300°F. to cure the adhesive. Masking varnish had to be used in liberal quantities on various parts before putting the core and coils in the oven so that undesirable adhesion of various members would not occur.

This type of construction worked very well, the main objection being that if not supported properly, the core and coils tended to sag a little bit in the oven while the lamination adhesive was undergoing cure.

We see no reason why it would not be possible to construct these two transformer units without using a curing oven. It would be possible to use insulated bolts such as nylon bolts instead of adhesive for holding the laminations together. Air curing varnishes are, of course, available for impregnating the transformer power coils if an oven is not available for oven curing.

There were no real serious engineering problems encountered in designing or building these two transformer units. The most bothersome problem was determining what kind of wire to use for the single turn search coils. We found that ordinary magnet wire whether of formvar or polyester insulation lasted about five minutes when used as single turn search coil. Apparently these coils are subjected to some sort of abrasion during the winding process, and also possibly during the operation of the transformer due to vibration of the iron laminations when the transformer is energized. We also used a small wire insulated with a plastic insulation. This was much better than ordinary magnet wire but was not suitable for the operating heat which was sometimes encountered when using the transformers. We are now trying heavy poly-thermaleze* Double Daglas* wire for use for the single turn search coils. For the ten-turn search coils which went around the outside of the iron core, there seemed to be no particular difficulty as ordinary magnet wire seemed to be all right for this purpose.

The use of six coils instead of four coils with two of the six coils on the two end core portions necessitated a construction which considerably increased the leakage reactance of the transformer coils for the single core, single phase transformer. The method of assembly used was to assemble the core and coils with three coils on each side of the transformer and then to move two of the coils around a corner to the end core portion. This necessitated using more wire for the end coils although they had the same number of turns as the other four coils. Also, larger clearances between core and coils were necessary for the end coils; all of which enlarged the

* Phelps Dodge Corporation, registered trademark.

length of the magnetic circuit without any particular compensating advantage. Future models of the single core, single phase transformer will be built using only four coils.

To summarize, we believe that these two special laboratory type transformers can be constructed in most of the electrical engineering shops encountered in a typical engineering school. Our prototype units were, in fact, constructed during the few weeks that we were eliminating various engineering difficulties and awaiting the arrival of necessary special material ordered for the construction of the torque demonstration units to be described in the next part of this report.

TORQUE DEMONSTRATION EQUIPMENT

One of the principles emphasized in the treatment of rotating electric machines in modern electrical engineering textbooks[1,2] is that the developed torque is given by an expression of the form:

$$T(\theta) = \frac{1}{2} \sum_{j=1}^{n} \sum_{k=1}^{n} i_j i_k \frac{d(L_{jk})}{d\theta} \text{ newton- meters}$$

where: $n =$ total number of rotor and stator windings

$T(\theta)$ = developed torque in newton-meters at position θ for the n winding system.

θ = angular position of the rotor measured in mechanical radians from a convenient zero point.

L_{jk} ,($j \neq k$) is the mutual inductance between windings j and k at a specified value of θ. These terms where $j \neq k$ give "excitation" torques.

L_{jj}, ($j=k$) is the self inductance of winding j at a specified value of θ. Terms involving the self-inductances give "reluctance" torques.

i_j and i_k are the instantaneous values of currents in winding "j" and "k" respectively. The windings may be located on either the rotor or stator.

In practice many of the terms in the above summation drop out because one or both currents may be zero or because $d(L_{jk})/d\theta = 0$.

We had felt for some time that it would be desirable to demonstrate the above principles in our electrical engineering laboratories.

A couple of years ago, we took two 3 phase, six pole, wound rotor induction motors and constructed equipment for measuring the static torque of these motors. The equipment required to do this was very simple and inexpensive. In Figure 17 a student is shown measuring the torque developed by one of these motors. Figure 18 shows a view of the equipment used for this purpose with the parts disassembled. An aluminum disc, about

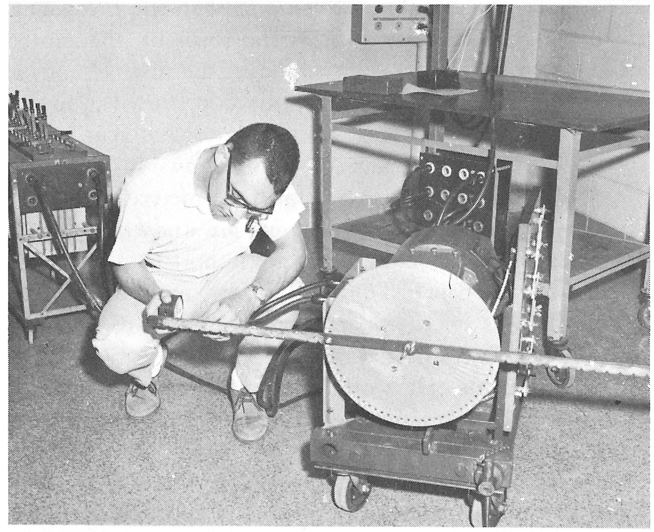


Fig. 17. Measuring the static torque of a 3 phase, 3HP, 6 pole wound rotor induction motor.

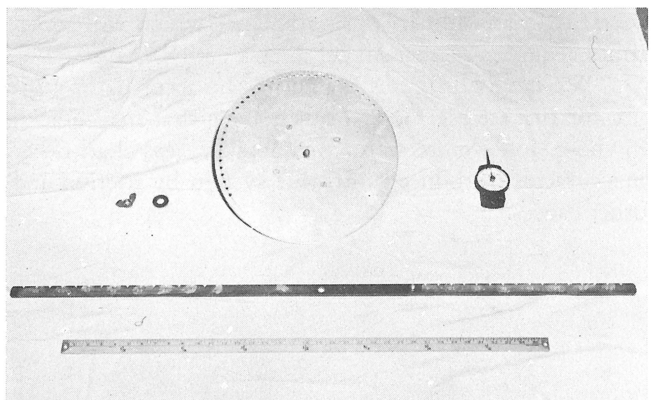


Fig. 18. Torque arm, disk, and force meter used for measuring torque of the 3 HP, 6 pole induction motor.

15 inches in diameter, was mounted on a steel hub, the hub being arranged to fit over the shaft of the motor being tested. A number of quarter inch diameter holes were drilled in the disc at 5 degree intervals (mechanical degrees). The holes were numbered for identification purposes, and covered about half of the circumference of the disc. The steel strap about four feet long was notched and arranged to serve as a torque arm. This torque arm was mounted on the aluminum disc by means of a wing nut. The position of the torque arm with respect to the circumference of the disc could easily be changed by loosening the wing nut. A metal pin going through a hole in the torque arm and fitting into one of the holes at the edge of the disc fixes the location of the torque arm with respect to the disc and rotor. A force meter could then be used to measure the force exerted by the torque arm when the motor was energized. Notches were cut in the torque arm at marked inch intervals so that the torque could easily be computed from the force meter reading and a knowledge of the distance out from the center of the shaft. In the operation of this equipment,

[1] Fitzgerald and Kingsley, "Electric Machinery", McGraw-Hill Book Co., 2d edition, 1961, Chapters 2 and 3.

[2] White and Woodson, "Electromechanical Energy Conversion", John Wiley and Sons, 1959.

the torque arm should always be kept in the horizontal position and the position of the rotor of the motor changed by using a different hole in the disc. Usually a mechanical stop such as a piece of wood is used to insure that the student operator keeps the torque arm in the horizontal position. Such a stop is not shown in Figure 17.

Figure 19 shows the type of force meter for making force measurements. These meters are known as Scherr Precision Dynamometers. They are imported from France and sold by the Scherr-Tumico, Inc., St. James, Minnesota. These devices were apparently developed to measure small forces encountered in relay and other mechanical type movements. They can be obtained calibrated either in ounces or grams. If properly used, these devices can give consistent results in the undergraduate laboratory when performing the tests described. The use of these force meters in combination with a variable torque arm is a convenient way of measuring static torque. This type of force meter is also relatively inexpensive, costing about $30 a piece. These particular devices seem to work much better than an ordinary spring balance which will sometimes acquire a permanent set after a period of use.

We have no figures regarding the accuracy of reading for these force meters, but believe that inaccuracies in these force meters are considerably less than other inaccuracies introduced into this system by friction and other causes.

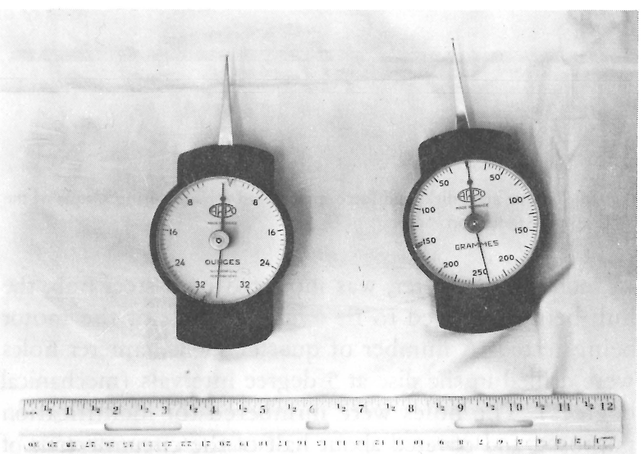


Fig. 19. Force meters used for static torque measurement.

Figure 20 shows the type of test results obtained using the 3 hp six pole, 60 cycle motor mentioned above.

The lower curve of Figure 20 shows the results of the torque tests with one phase of the 110 volt, 3 phase, star connected stator of the induction motor connected in series with two of the rotor terminals. The mutual inductance curve shown at the top of Figure 20 was obtained by exciting the stator phase with alternating current, 60 cycles, and measuring the open circuit voltage across the two rotor terminals used in the torque test. The arrangement described above for demonstrating torque in a rotating machine had the advantage of simplicity, low cost, and utilization of existing laboratory equipment, namely the 3 hp induction motor. We tried extending this method to other machines in our laboratory but without very much success although we were able to demonstrate reluctance torque in one or two of our direct current machines which did not have interpoles.

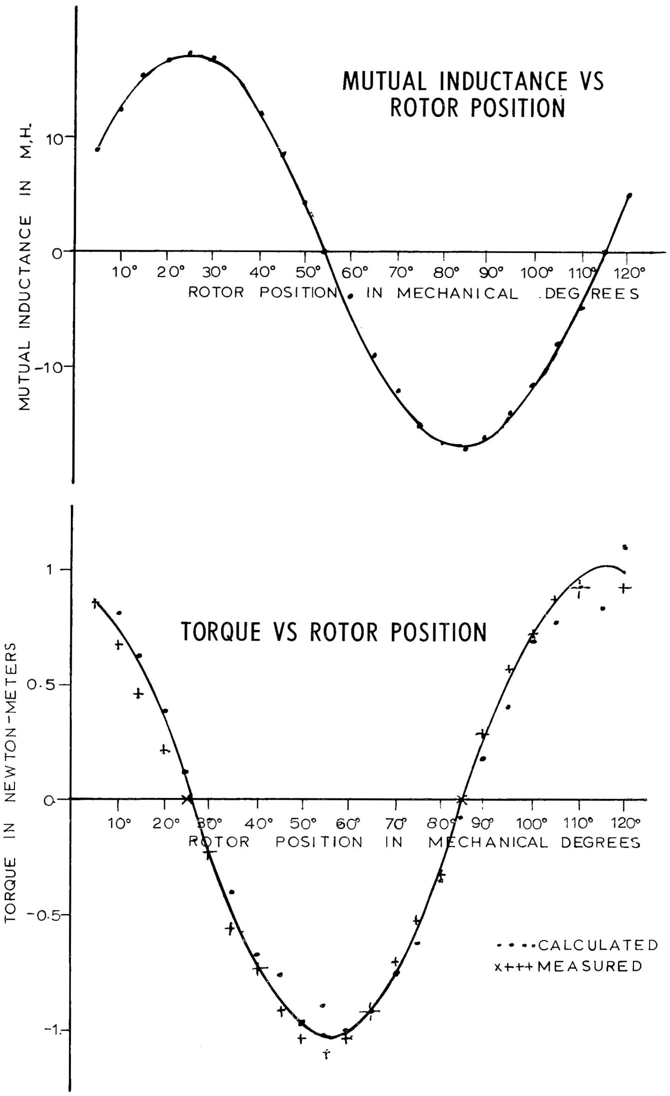


Fig. 20. Results of static torque tests on 3 HP, 6 pole, wound rotor motor.

We found that it was absoultely necessary to use ball bearing machines for this type of test. Sleeve bearing machines had too much friction and the errors of torque measurement were accordingly too large to give good results.

We were not able to demonstrate reluctance torque in any of our laboratory salient pole synchronous machines because they had sleeve bearings. In such machines we had to use a flux meter to determine inductance instead of using the a-c circuit methods which could be used for the wound rotor motor. This was on account of the damper windings on the synchronous machines.

After a certain amount of practical experience, we decided that flux meters were not desirable for use in most undergraduate engineering laboratories on account of their relative fragility.

CONSTUCTION OF LABORATORY TORQUE DEMONSTRATION MODELS

We wanted to construct something more suitable for demonstrating electromagnetic torque than the use of the 3 hp commercial induction motor as was outlined in the preceding paragraphs. Figure 21 shows a rough sketch of the arrangement proposed for this purpose. The rotor was to be mounted on a vertical shaft and to be easily removable. A ball thrust bearing was provided at the bottom to take the weight of the rotor and a Teflon guide bearing supported the top of the rotor shaft. An arrangement was to be provided for supporting a Hall effect wafer in the air gap for measuring air gap magnetic flux densities. The support for the Hall effect wafer was to be movable so that the wafer could be moved around the air gap and the curve of flux density versus air gap position obtained by test. Figure 21 is only a diagramatic sketch showing the proposed basic arrangement and does not pretend to show details such as dial scales for indicating position, windings, mechanical supports, etc. The idea for using the Hall effect wafer in this manner was not original with the authors. Professor H. W. Bibber of Union College, Schenectady, New York, used this construction several years ago in his laboratory. We believe that he modified an existing, old type of d-c machine for this purpose.

In order to obtain as much experience as possible we constructed four different stators and four different rotors.

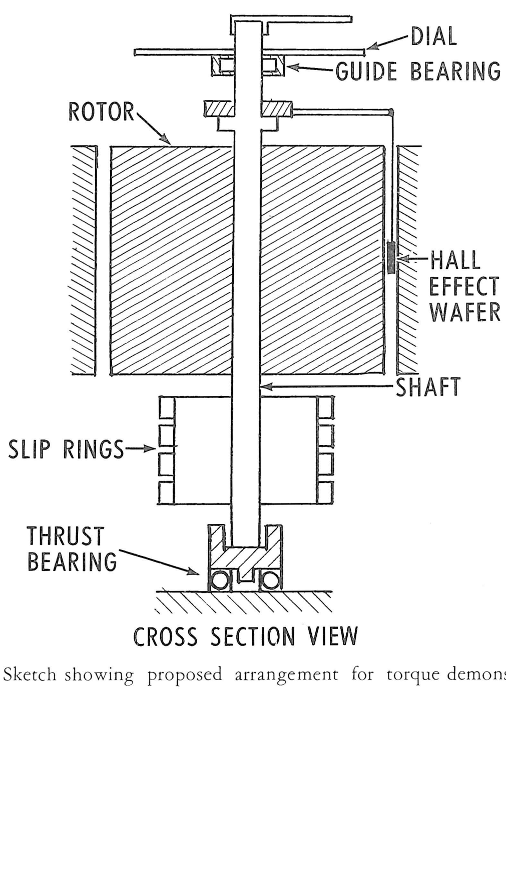


Fig. 21. Sketch showing proposed arrangement for torque demonstration devices.

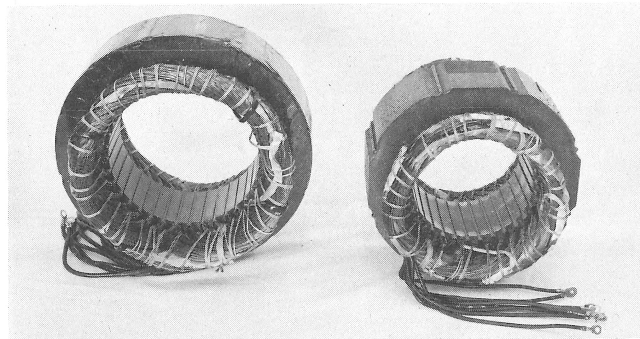


Fig. 22. View of unmounted shell type wound stators 10 HP unit on the left. 7.5 HP unit on the right.

Two of the stators were wound stators and the other two were salient pole stators. Likewise, there were two cylindrical rotors and two salient pole rotors.

Wound Stator Construction:

For the wound stator units we purchased two shell type wound stators. Both of these units were two pole, two phase, 220-440 volt units. One stator unit was rated at 10 hp and we designated this unit as model B-10 to differentiate it from the smaller unit which was rated at 7½hp and which was designated as model A-7.5. The salient pole stator units and the rotors were also given these designations. This meant that either of the model B-10 rotors would fit into either of the two model B-10 stators and likewise for the model A-7.5 units.

Figure 22 shows a view of the two shell type stators used for the wound stator units. Model A-7.5 is on the right side of the picture, and model B-10 is on the left side of Figure 22.

Each of the stators was assembled in a supporting angle iron framework mounted on casters. A steel cup was fitted into the ball thrust bearing at the bottom of the supporting frame. The rotor shaft fits into this cup, thus protecting the bearing. The guide bearing consisted of a small Teflon cylinder inserted in a hole, supported by a cross member which was fastened to the frame by two bolts. To change a rotor it was only necessary to undo the two bolts of this cross member at the top of the supporting framework, lift the brushes from the brush holders, remove the rotor, and then insert a new rotor.

Figure 23 shows a top view of one of these stators mounted in the supporting frame without any rotor. Figure 24 shows a rear view of the stator mounted in the supporting framework without any rotor. Here one can see the steel cup and the ball thrust bearing at the bottom of the framework for supporting the rotor. The brush holder supports can also be seen. Figure 25 shows the rear view of an assembled wound stator unit with the rotor inserted and ready for use. A good view of the rotor slip rings can be seen at the bottom of the unit.

Figure 26 shows the assembled wound stator with its rotor inserted. This view shows the type of aluminum terminal board employed for the two phase stator wind-

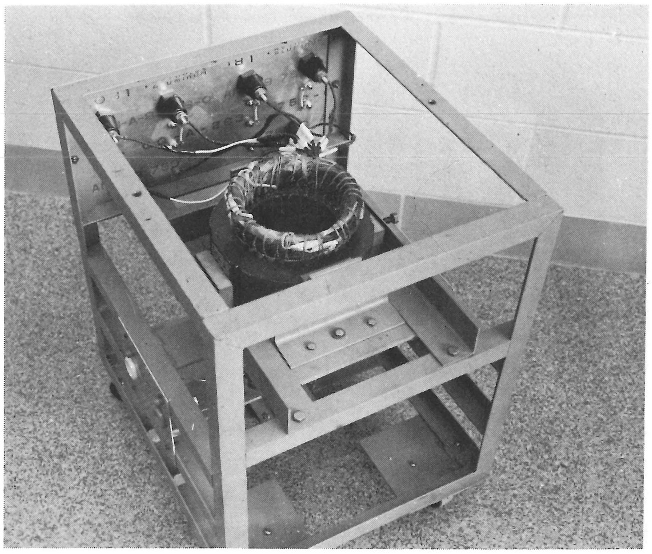


Fig. 23. Wound stator mounted in supporting frame with rotor removed.

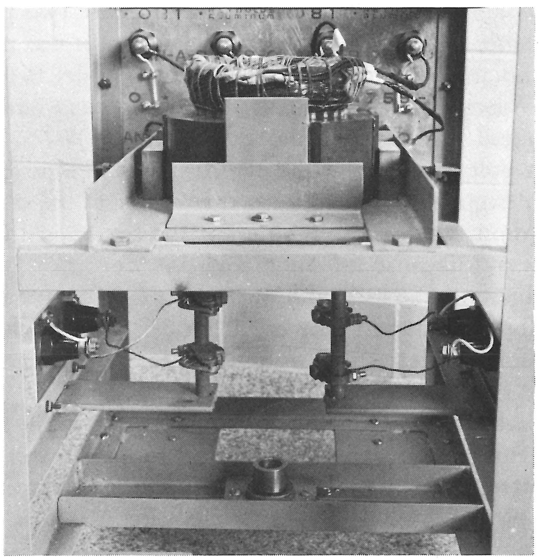


Fig. 24. Rear close up view of wound stator shell mounted in supporting frame. Rotor removed.

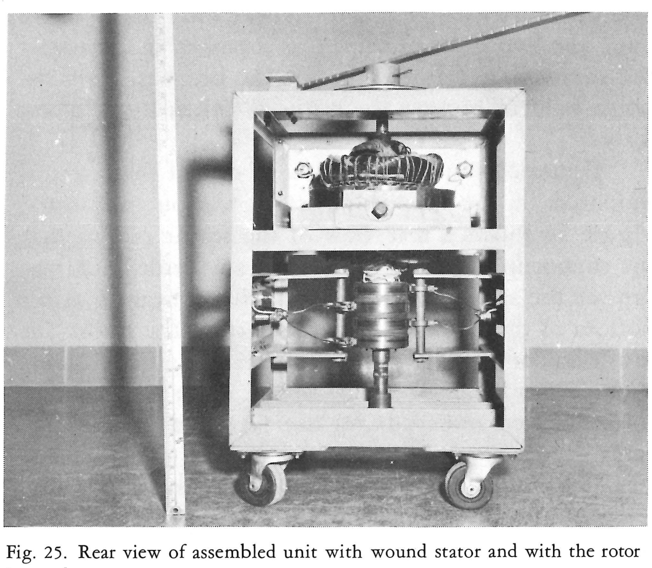


Fig. 25. Rear view of assembled unit with wound stator and with the rotor inserted.

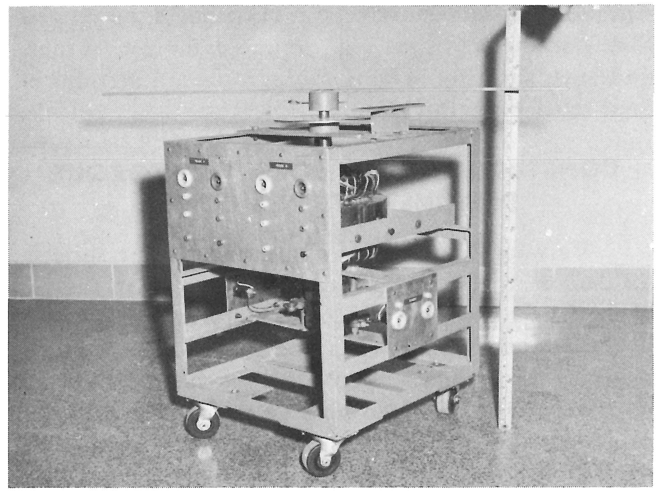


Fig. 26. Assembled view of wound stator unit showing front and side terminal boards.

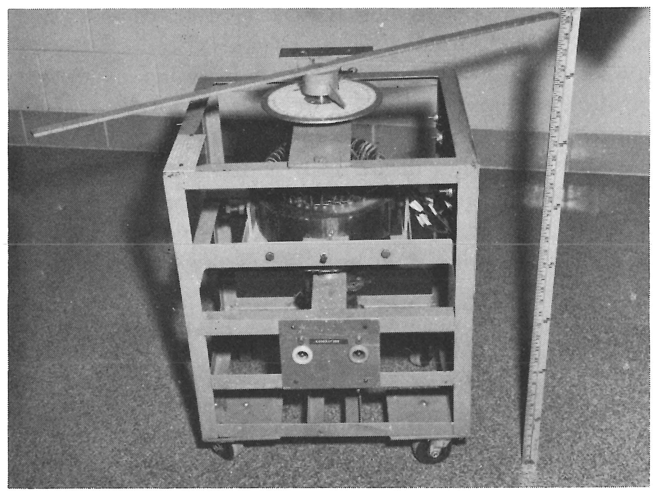


Fig. 27. Top and side view of wound stator unit showing torque arm and circular scale.

ing. For the rotor windings a terminal board with two terminals was mounted on each side of the unit.

Figure 27 is a top, side view of the unit showing arrangement of the torque arm and circular dial scale at the top of the unit.

Figure 28 shows a view of the torque arm, top bearing mount, and circular scale for measuring the rotor position. The top bearing mount has already been described. The torque arm simply consists of a steel strap with notches cut at marked inch intervals and with a pointer welded to the hub supporting the torque arm.

The dial scale construction is worth nothing. It consists of an aluminum dial upon which has been fastened a paper scale graduated in 360 one degree divisions. To protect the paper disk from wear, .05" thick cellulose acetate film was placed over the paper dial.

The cellulose acetate film is easily cut in the form of a circle by using ordinary scissors. It does have the disadvantage of dimensional instability. We found that in humid weather, the cellulose acetate film would expand and work loose from the scale. Eventually it was found necessary to hold the acetate film down on the disk with small bolts.

To eliminate the difficulties encountered with the cellulose acetate film we tried using some 0.06" thick acrylic film. This is not as sensitive to humidity changes, but has to be shaped by hot working. We found that we could easily cut a circular disk of the acrylic film using an ordinary electric soldering iron as the hot tool. Epoxy adhesive (Hysol Epoxi-patch Kits #1C White and #0151 Transparent) were used to fasten the aluminum base plate disk, the paper dial, and the protecting acrylic film together. If more than one torque demonstration unit is to be made, the best way is to either have a good draftsman make a suitable large size dial or to photograph some existing dial using a Xerox machine.

We were able to construct a relatively inexpensive dial, 7.5" in diameter and graduated with 360 one degree divisions. The dial was located and fastened on the removable bearing mounts by four removable pins.

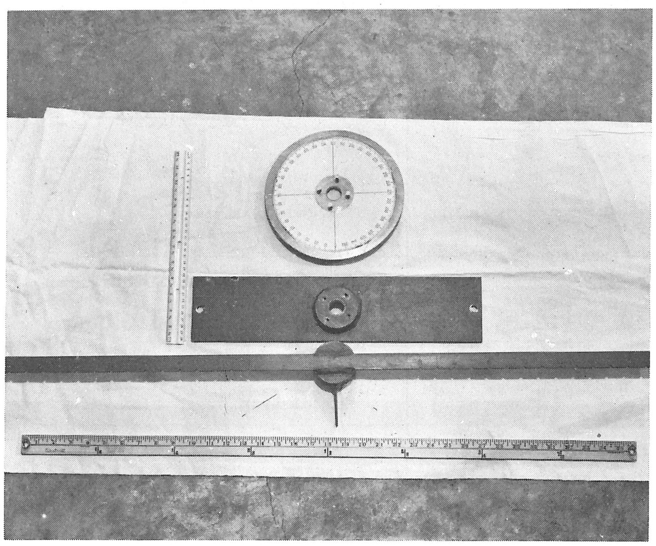


Fig. 28. Circular scale, top bearing mount, and torque arm.

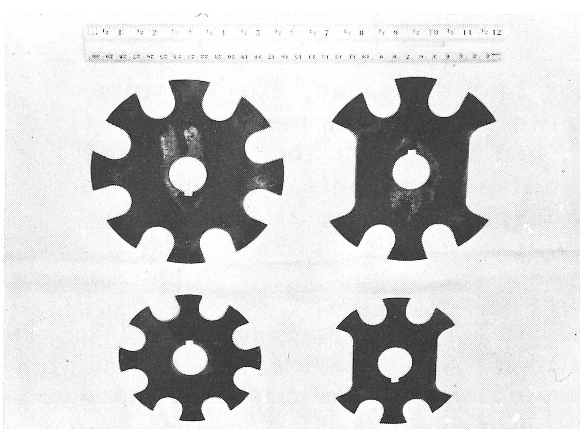


Fig. 29. Rotor laminations used for the four types of rotors. Model B-10 at top. Model A-7.5 at bottom, Cylindrical rotor punchings on left. Salient pole punchings on right.

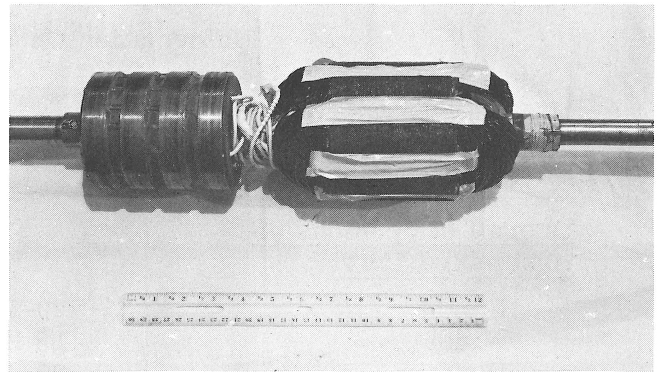


Fig. 30. Completely assembled cylindrical rotor.

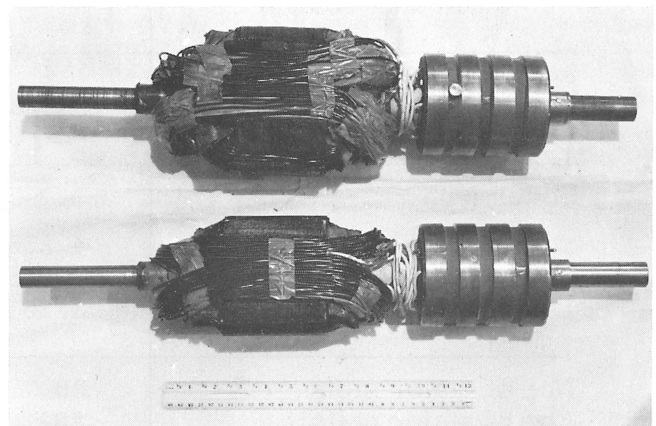


Fig. 31. Completely assembled salient pole rotors.

Technical information including dimensions, for the Model A-7.5 and Model B-10 wound stator units is given in Table III.

Rotor Construction:

Figure 29 shows the types of rotor laminations used in the four different rotors which were constructed. The two larger diameter rotors at the top were used in the Model B-10 stators. The two smaller diameter laminations at the botttom of Figure 29 were used in the Model A-7.5 stators. The salient pole rotor laminations were the same as the cylindrical rotor laminations except that two of the teeth were cut off as can be seen from Figure 29. Table IV gives technical information for all four rotors.

Figure 30 shows the picture of a completely assembled cylindrical rotor complete with slip rings and mounted on the shaft. Figure 31 shows a picture of the two salient pole rotors completely assembled. The upper rotor in this picture is Model B-10 and the lower rotor in the picture is Model A-7.5.

As it is difficult to purchase rotor slip rings in small quantities at low prices, and as we wanted four slip rings instead of three, the rotor slip rings were constructed in our own shop.

We used 3½" SPS extra heavy Anaconda Copper Bus Pipe, 4" outside diameter. This pipe was sliced into

Table III
Information On The Wound Stator Units

Stator Unit	Model A-7.5	Model B-10
Overall dimensions of Assembled Unit		
Height	29-7/8 inches	30-1/8 inches
Width	18 inches	18 inches
Depth	20 1/4 inches	20 1/4 inches
Estimated Weight (excluding rotors)	130 pounds	145 pounds
Stator rating as a 2 Pole Motor	7.5 HP	10 HP
Stator Iron		
Stator Bore (I.D.)	4.875 inches	6.125 inches
Stator Outside Dia.	8.5" - 8.75"	10.53 inches
Length of Stator Iron	3.25 inches	2.80 inches
No. of stator slots	30	36
No. of stator coils	28	36
Approx. turns per coil	About 20	About 15
No. of coils/polar group	7	9
Wire size (round)	#16 and #21 in parallel.	Two #15 in parallel.
Total conductor cross-sec.	3395 CM	6520 CM
D. C. resistance per phase, with both polar groups in series at 20°C	2.31 ohms/phase	1.32 ohms/phase
Nominal continuous current rating per polar group	5.0 amps	6 amps

Note: Both of these wound stators are wound for 2 pole, 2 phase, 220-440 volts, 60 cycles. The windings are double layer with two polar groups per phase.

The number of slots, coils, turns per coil, and wire sizes were determined as well as possible from a careful examination of the actual units. The manufacturer did not furnish information concerning these quantities.

The insulation is Class A.

widths suitable for slip rings. Short lengths of fiber board tubing were used as spacers between the four slip rings. Leads were soldered to each of the four copper rings and fiberboard disks were used to close the ends of the assembly, which was mounted on a piece of steel tubing, These various pieces were assembled together and held in place with pressure-sensitive tape. Epoxy resin was poured into a hole at one end and when this resin solidified by room temperature curing we had a solid mass consisting of four insulated slip rings with leads brought out at one end and mounted on a steel tube. The steel tube could fit over part of the rotor shaft.

Table IV
Information on Rotors

	Cylindrical Rotor Model A-7.5	Salient Pole Rotor Model A-7.5	Cylindrical Rotor Model B-10	Salient Pole Rotor Model B-10
Rotor Iron Core				
Number of laminations	About 246	246	About 206	210
Core length	3.75 inches	3.75 inches	3.125 inches	3.125 inches
Outside Diameter	4.625 inches	4.625 inches	5.875 inches	5.875 inches
I. D. for shaft mounting	1.125 inches	1.125 inches	1.125 inches	1.125 inches
D Axis Winding	Two coils in series, each coil wound with 72 turns of #14 round wire for a total of 144 turns in 4 slots.	One coil of 140 turns of #12 round wire. Random wound in two large slots.	Two coils in series, each coil wound with 83 turns of #12 round wire for a total of 166 turns in 4 slots.	One coil of 150 turns of #12 round wire in two large slots.
Q Axis Winding	Two coils in series, each coil wound with 72 turns of #14 round wire for a total of 144 turns in 4 slots.	Two coils in series in 4 slots. Each coil has 72 turns of #14 round wire for a total of 144 turns in series.	Two coils in series, each coil wound with 83 turns of #12 round wire for a total of 166 turns in 4 slots.	Two coils in series in 4 slots. Each coil has 75 turns of #12 round wire for a total of 150 turns in series.

Note: Rotor insulation for all rotors was Class 130. One coil side in each rotor slot. Rated rotor current input same as stator rated current per stator coil in which the rotor is mounted. Model A-7.5 rotors weigh approximately 30 pounds each. Model B-10 rotors weigh approximately 40 pounds each. These weights include shafts, slip rings, iron core, and windings.

We made four of these slip rings using one gallon of ERL - 2795 Bakelite Epoxy Resin with 1 quart of ERL - 2793 Hardener.

As mentioned previously, any of the two model A-7.5 rotors could be used with either of the Model A-7.5 stators and simularly for the Model B-10 units.

The brush holders used for the slip rings were Phoenix Electric Mfg. Co., #20010 and these were mounted on hard fiber rod as shown in Figure 25.

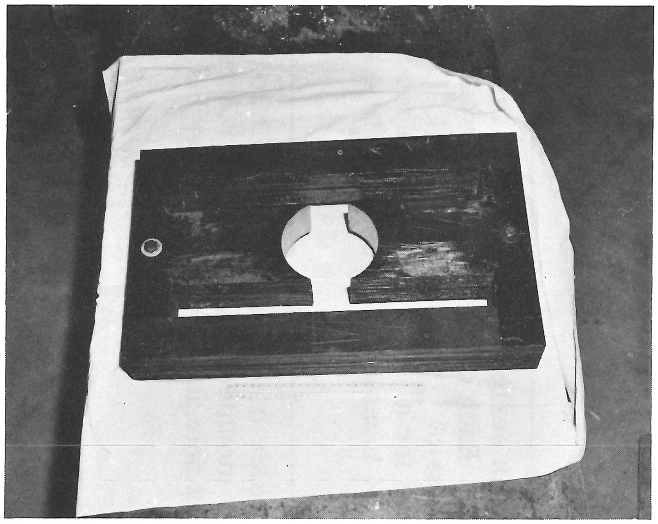


Fig. 32. Laminated magnetic circuit of Model B-10 salient pole stator.

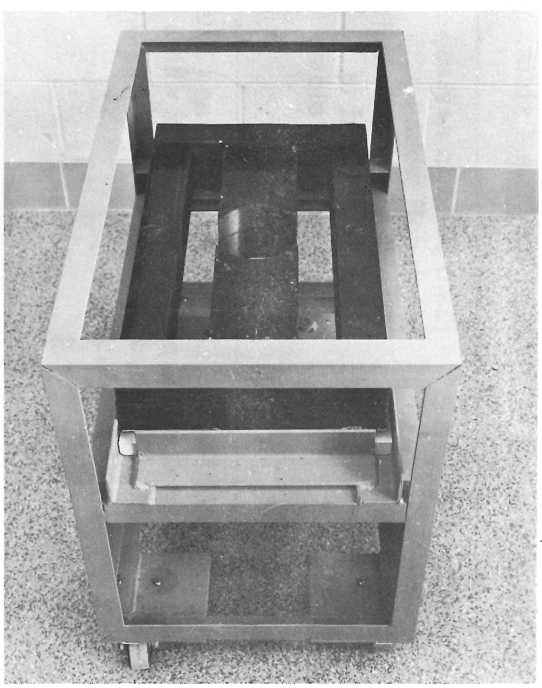


Fig. 33. Laminated magnetic circuit of Model A-7.5 salient pole stator mounted in supporting frame.

CONSTRUCTION OF THE SALIENT POLE STATORS

Figure 32 shows a view of the magnetic circuit of one of the two salient pole stators. A picture of one of these stators supported in its framework before the coils have been installed is shown in Figure 33. It is worth noting at this point that the laminations for the salient pole stators and for all four rotors were fastened together using adhesive as was done for the transformer units described in the eariler part of this report.

Table V gives some technical information for the Model A-7.5 and Model B-10 salient pole stator units.

Figure 34 shows the top rear view of the Model A-7.5 salient pole stator unit completely assembled. The dial and torque arm-pointer assembly for the salient pole units is interchangable with the similar parts used on the wound stator machines. In fact the four shafts for all of the rotors were turned to the same dimensions.

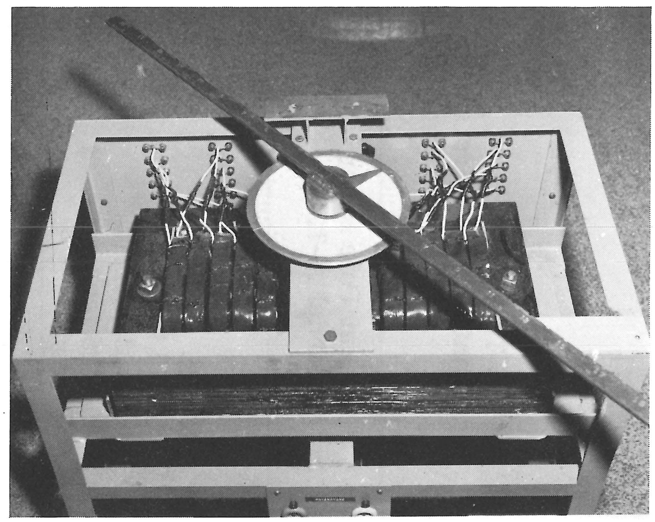


Fig. 34. Top rear view of Model A-7.5 salient pole stator assembled with rotor.

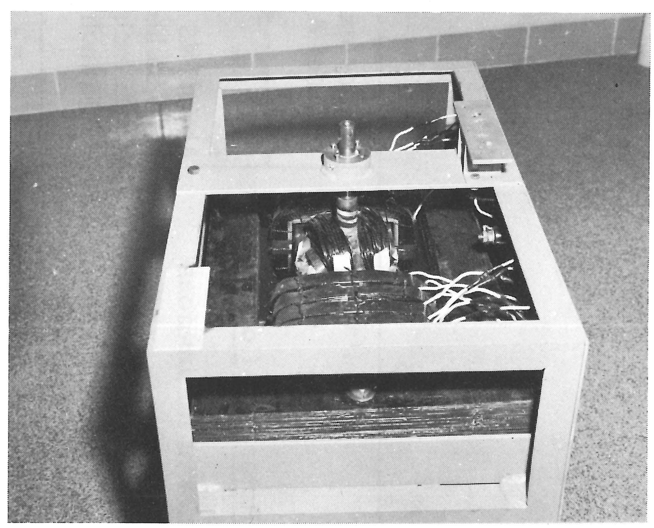
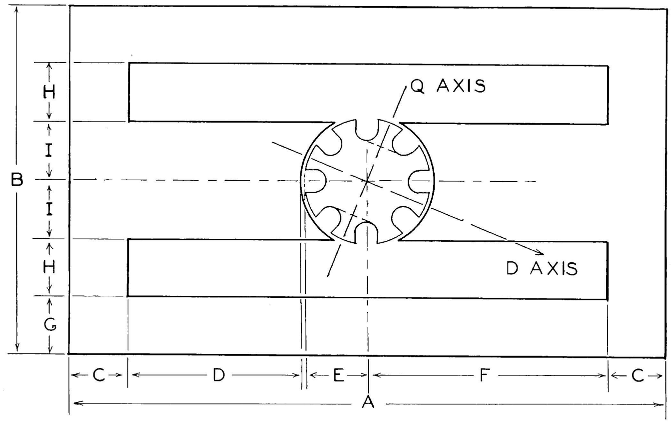


Fig. 35. Side top view of Model B-10 salient pole stator with dial and torque arm removed.

Table V
Information On the Salient Pole Stators

	Model A-7.5	Model B-10
Overall Dimensions Assembled		
Height over torque arm	29 7/8 inches	30 1/4 inches
Width over frame	30 inches	30 inches
Depth over frame	18 1/4 inches	18 1/4 inches
Estimated Weight (excluding rotors)	345 pounds	405 pounds
Stator Iron		
Number of laminations thick	240	200
Measured Axial length	3.75 inches	3.125 inches
Stator bore (I. D.)	4.875 inches	6.125 inches
Estimated Weight of Stator Laminations	201 pounds	229 pounds
Stator Windings		
Consist of 10 duplicate coils, 5 coils on each pole		
Turns per coil	160	110
Wire size (Round)	No. 14	No. 12
Approx. Weight per coil	3.75 lbs.	4.7 lbs.
Resistance per coil at $20^{\circ}C$	0.767 ohms	0.360 ohms
Current rating per coil, $75^{\circ}C$ rise, continuous	4.5 amps	6.7 amps
Insulation	Class 130	Class 130



ALL DIMENSIONS IN INCHES	A	B	C	D	E	F	G	H	I
MODEL A 7.5	23.	13.5	2.25	6.8125	2.3125	9.25	2.25	2.25	2.25
MODEL B 10	25.18	15.86	2.59	6.9	2.9375	10.0	2.84	2.25	2.84

Fig. 36. Dimensions of the magnetic circuits for the salient pole stators.

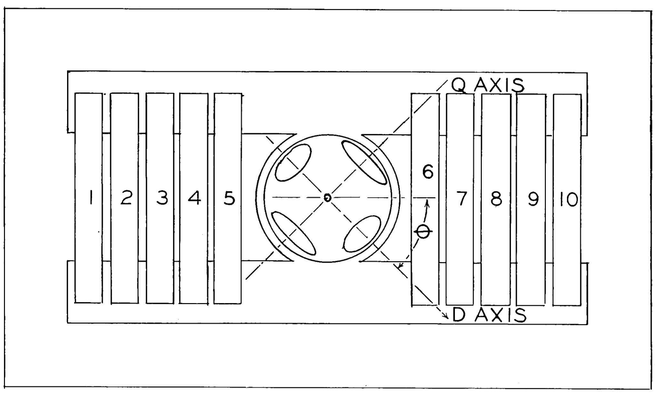


Fig. 37. Coil arrangements and indentifications for the salient pole stators.

Figure 36 shows the dimensions of the plan view of the magnetic circuits for the Model A-7.5 and Model B-10 salient pole stators. Figure 37 shows the coil numbering system for the ten stator coils of the salient pole stators and also the D axis and Q axis for the rotors. For all stators and rotors the wiring is arranged so that when positive directed currents go into the D axis terminals and into the stator positive terminals the MMF's will add and the rotor D axis will tend to line up with the excited stator axis.

For salient pole rotors the D axis is always along the path of least reluctance or the portion with the smallest air gap. The Q axis rotor winding is always located at right angles to the D axis winding and acts along the path of greatest reluctance. Figure 35 shows a top end view of the model B-10 salient pole stator with rotor inserted but with the top dial and torque arm removed. Figure 38 shows a rear view of the Model A-7.5 salient pole stator completely assembled with rotor. Figure 39 shows the side view of one of the salient pole stators completely assembled with its rotor. Figure 40 shows the front view for a completely assembled salient pole stator with rotor. A good view of the front terminal board is shown in this picture. There are two banana jacks for each coil terminal of the ten stator coils. The coil leads for the rotor D-axis winding are brought out from the slip rings to the lower terminal board. The two coil leads for the Q-axis rotor winding are brought out to a terminal board in the rear. All terminals are marked so that the student can easily see what they are, and so that he can trace out the connections if he desires to do so. The two 100 amp receptables in the center of the front panel with associated banana jacks are intended for use in making cross connections and also for bringing in power from a standard laboratory supply using standard laboratory 100 ampere plugs.

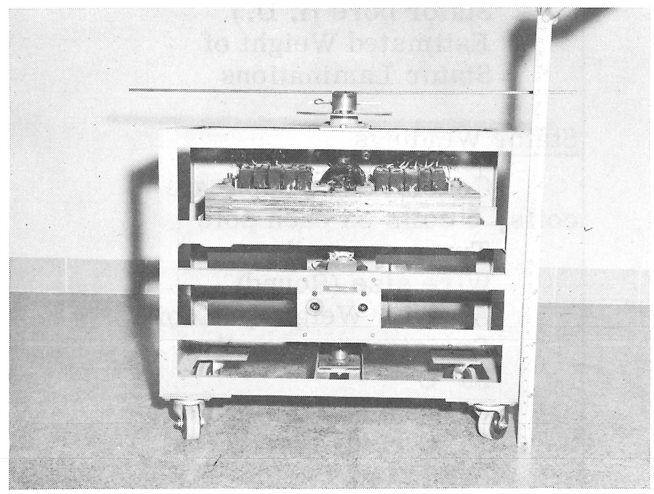


Fig. 38. Rear view of completely assembled Model A-7.5 salient pole stator.

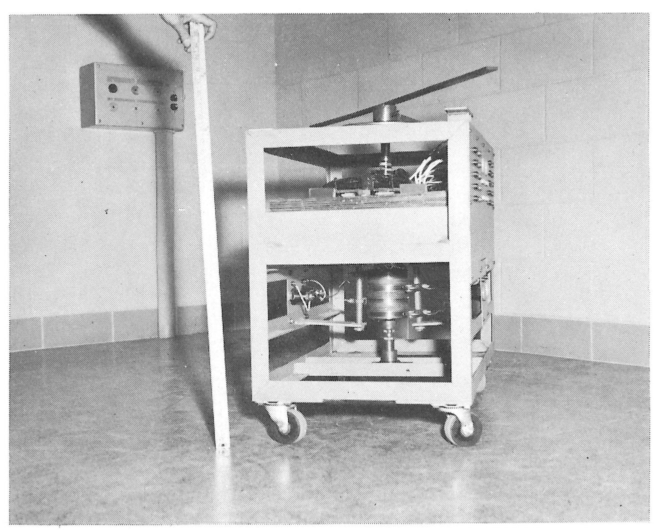


Fig. 39. Side view of completely assembled Model B-10 salient pole stator with rotor inserted.

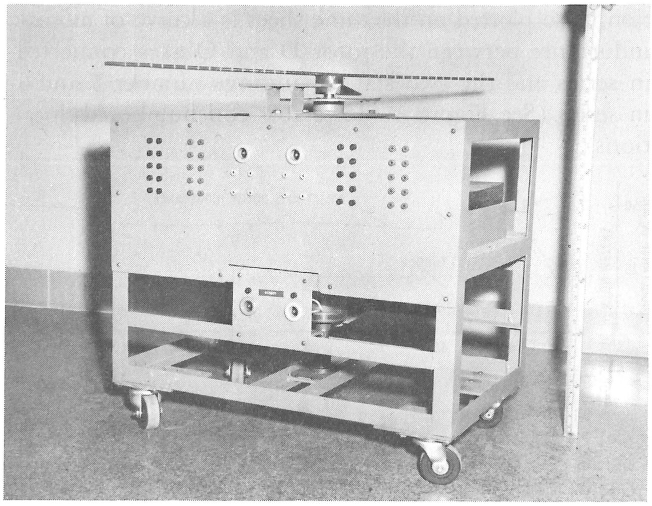


Fig. 40. Front view of completely assembled salient pole stator unit, showing the front terminal boards.

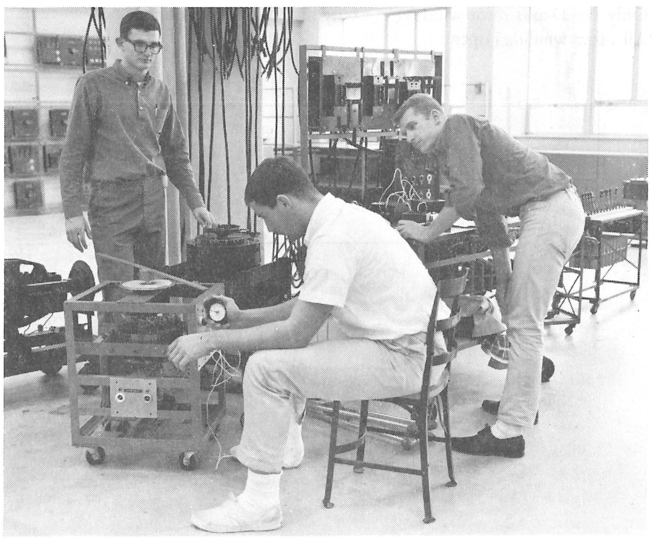


Fig. 41. Class testing one of the wound stator torque demonstration units.

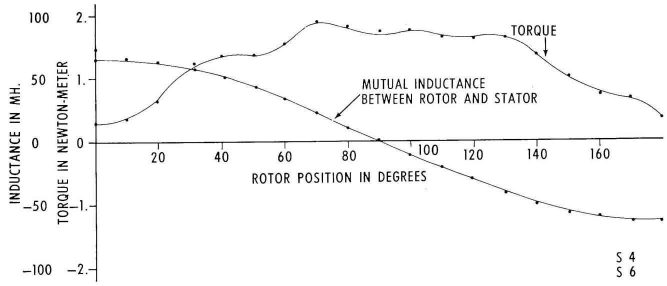


Fig. 42. Test results for a model B-10 wound stator with a cylindrical rotor. The D and Q rotor axes are in series with each other and with Phase A of the stator. A direct current of 4 amperes is flowing through these windings for the torque curve shown.

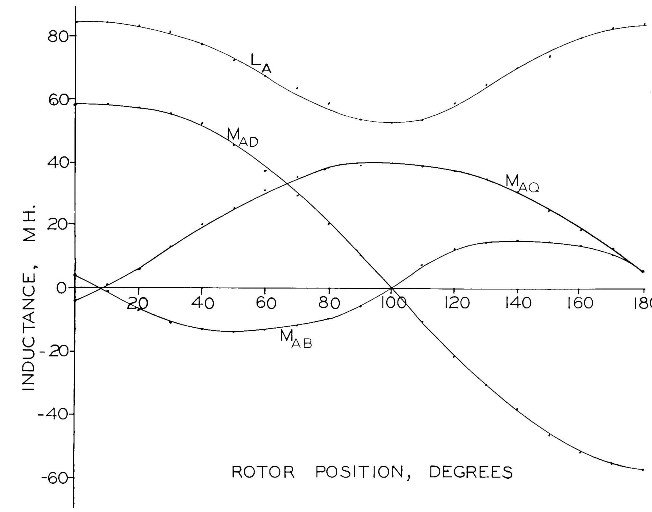


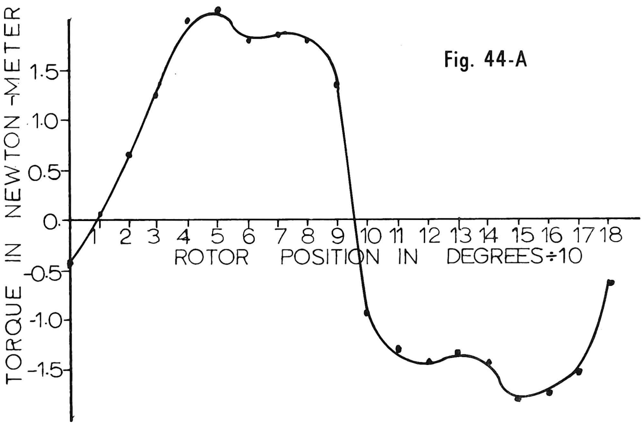
Fig. 43. Results of inductance measurements taken at different rotor positions for the windings of the Model B-10 wound stator with the salient pole rotor inserted. The inductances, L_B, M_{BD}, and M_{BQ}, with the stator phase B would be the same as shown for the inductances L_A, M_{AD}, and M_{AQ} except displaced 90° in space.

TESTS ON THE TORQUE DEMONSTRATION UNITS

A large number of tests were made using different combinations on the torque demonstration units. Figure 41 shows a group of students conducting a test during a laboratory class. Space is not available in this report to do more than give a small sample of a few of these tests. Figure 42 shows the results of some tests on the Model B-10 unit with a wound stator and the cylindrical rotor. The D and Q axes on the rotor were connected in series with each other and in series with phase A of the stator. One curve shows the variation of mutual inductance between the stator A phase and the D and Q axes rotor windings in circuit. The other curve is a curve of torque against rotor position in degrees with 4 amperes direct current going through the phase A stator windings in series with the two rotor windings. The irregularities in the torque curve may be due to measurement errors caused by friction, or possibly by the large rotor slots.

Figure 43 applies to the combination of a Model B-10 wound stator with a corresponding size salient pole rotor. For this set of curves, phase A of the wound stator was excited with alternating current and from a-c circuit measurements, various inductance quantities could be determined for different rotor positions. In this way, the self inductance of phase A of the stator, mutual inductance M_{ad} and M_{aq}, from phase A of the stator to the rotor windings, and M_{ab}, mutual inductance between phase A and phase B on the stator, were plotted against rotor position.

Figure 44-A for the same machine shows a curve of reluctance torque plotted against rotor position with stator A phase excited with a direct current of 10 amperes and all the other windings of the machine open circuited. The brushes were lifted for the test of figure 44-A to reduce friction.



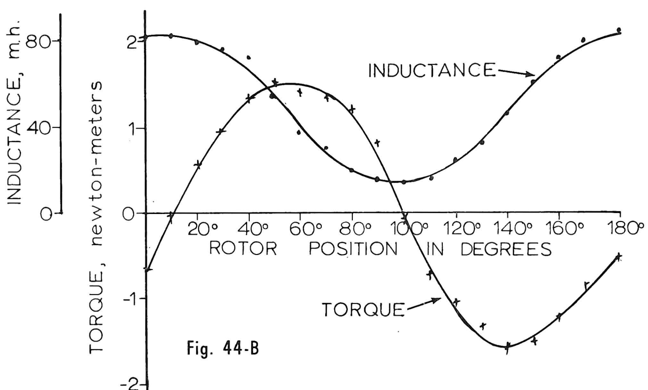


Fig. 44. Results of torque tests taken on the Model B-10 wound stator with a salient pole rotor. Measured inductance values for this combination shown in Figure 43.

Figure 44-B shows a test on the same machine with the brushes down and with the Q rotor axis short circuited and with 6 amperes a-c in the A phase. Both the apparent self inductance of the A phase and the torque developed are plotted in Fgure 44-B.

The test results shown in Figure 45 were taken with a Model B-10 salient pole stator and a salient pole rotor. On this graph, the self inductance of the D axis rotor winding is plotted against rotor position in degrees. The curve of torque against rotor position in this figure is the torque with the rotor windings of the D axis carrying 12 amperes direct current with all of the other windings on the machine open. Wiggles in the portion of this curve between 50 and 120 degrees were present in the corresponding set of curves taken from the Model A-7.5 machine and they may be due to physical irregularities in the self inductance curve, possible on account of the rotor slots.

The tests shown in Figures 46 and 47 were taken with a Model B-10 machine using a salient pole stator in combination with the wound rotor. In Figure 46 an alternating current of 5 amperes was sent through the D-axis rotor windings. All of the stator windings were open. At this constant value of alternating rotor current the curve of reluctance torque and self inductance of this rotor winding combination is plotted against rotor position. Also plotted on the same sheet is a curve of mutual inductance between the rotor D and Q axes connected in series and the two stator windings number 5 and 6 in series (See Figure 37 for stator coil numbered locations).

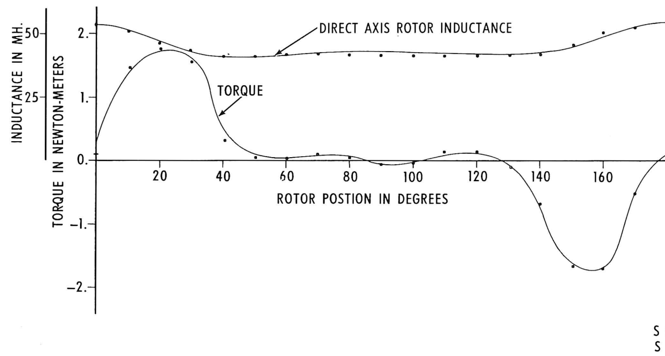


Fig. 45. Reluctance torque and self inductance curves for the D-axis rotor winding for a Model B-10 salient pole stator combined with a salient pole rotor. Only the D-axis rotor winding is excited with a direct current of 12 amperes. All other windings open.

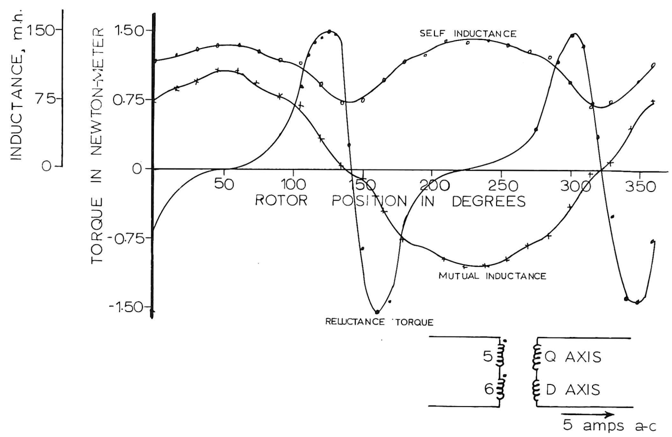


Fig. 46. Test results on Model B-10 combination consisting of a salient pole stator combined with a cylindrical rotor. Rotor D and Q axes windings are in series. All stator windings are open. The test curves include: Rotor self-inductance versus rotor position. Reluctance torque with 5 amps. a-c in the rotor versus rotor position. Mutual inductance between rotor windings in series and stator coils 5 and 6 connected in series versus position.

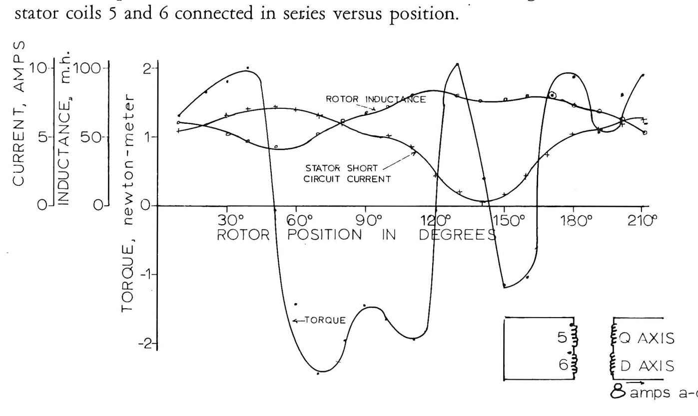


Fig. 47. Test results on a Model B-10 combination consisting of salient pole stator in combination with a wound rotor. Rotor D and Q axis windings are in series and carry 8 amps. a-c. All stator windings are open except stator coils 5 and 6 which are short circuited. Quantities plotted against rotor position are: Torque. Apparent rotor input inductance. Short circuit current in stator coils 5 and 6 connected in series.

In figure 47 the conditions for the same circuit are plotted except that the stator coils 5 and 6 are short circuited and 8 amperes alternating current are sent through the D and Q axes rotor windings in series. The short circuit current in the stator coils 5 and 6, the apparent self inductance of the input into the rotor windings, and the resulting torque are plotted against rotor position. Note the badly distorted shape of the torque curve which is typical of situations where one or more windings are short circuited.

Use In Class Instruction:

We were able to obtain almost two semesters of experience using the two wound stator units along with the cylindrical rotor units in our laboratory classes up to the time this report was written. Somewhat less than one semester was available for class testing the two salient pole stators with the two salient pole rotors. The student response to performing experiments with these torque demonstration units was about as follows:

1. They liked the experiment because they had a chance to check the textbook theory wherein the developed torque was a function of the product of two currents times the first derivative of an inductance with respect to angular rotor position. This was particularly true of the better students.
2. It was necessary to take a lot of test points in order to obtain a smooth curve of inductance and torque. This meant that a lot of routine and somewhat boring measurements had to be taken.
3. On account of a large amount of friction in the equipment the accuracy of the results in many cases was relatively low especially at the conservative value of currents which were specified by the instructor to be used during the experiment.

Class testing over a period of time is a very necessary process in the development of new types of laboratory equipment. From the above mentioned student reactions, it is obvious that engineering improvements are desirable in our first prototype model. The possibilities for this will be discussed later.

Since many of our students are familiar with programming of digital computers it might be possible and desirable to investigate the possibility of using the computer to work up the computations involved for the numerous experimental observations.

It took a typical group of students about one period to run one or two inductance vs. position curves plus one torque curve, as a lot of points were needed to obtain smooth curves. Since the inductance curves must be differentiated in order to compute the torque curves, a large number of inductance points are desirable.

With the class of equipment constructed it is possible to obtain all sorts of odd shaped torque vs. rotor position curves by exciting one or more winding and short circuiting one or more other windings, etc., and there are a large number of different combinations available. However, things get complicated very rapidly for the average undergraduate student. While many combinations of excited and short circuited windings are possible in the equipment which was developed, we feel that it is somewhat impractical to use very many of these in routine undergraduate laboratory instruction. Certainly if many such irregular winding and excitation combinations are used, a great effort on the part of the instructor is required in order to be sure that the student is enlightened rather than simply confused. However it is certainly worthwhile to perform at least the two simplest tests possible with the equipment which was built. A uniform air gap machine with one excited winding in the rotor and one excited winding in the stator is a basic combination. The determination of reluctance torque with a cylindrical winding excited, the other member having salient poles, can be used for the other basic test.

The limited classroom experience which we have had with the salient pole stator indicates that this stator is of less utility as regards demonstrating the development of torque than the wound stator. It is probable that the use of wound stators exclusively in combination with wound rotors and salient pole rotors would be sufficient to demonstrate most of the simpler types of torque development. The use of the salient pole stator in combination with a salient pole rotor gives plenty of reluctance torque but the shape of the torque versus rotor position curve is considerably different than would be expected from textbook treatments of this subject. Most textbook treatments are pretty well confined to only one of the rotor or stator members having salient poles and where machines having nice sinusodal shaped inductance curves can be assumed.

It is very easy to change from one rotor to another with a given stator in the type of construction employed. Probably less than five minutes time is required for the laboratory mechanic or an experienced undergraduate student assistant to change from one rotor to another. The terminal board arrangements for making connections to the torque demonstration units were flexible and easily understood by the student. We would not want to change them in future units particularly.

We could have used three phase wound stator units instead of two phase, but for instructional purposes this would simply have introduced additional complications with the possibility of confusing the student. We feel that it is probably more advantageous to use the two phase wound stators rather than three phase stators for this particular application.

On the whole we feel that the torque demonstration units were suitable for work in the classroom but that as actually constructed, a few minor modifications will be desirable, and instructional procedures will have to be developed in order to obtain maximum benefit from their use.

ENGINEERING AND CONSTRUCTION DIFFICULTIES

The torque demonstration units were considerably more expensive and more difficult to construct than were the two prototype transformers described in the first part of this report. It is really quite a task to assemble several of these units using student assistants working under the supervision of laboratory mechanic.

One of the difficulties encountered is that the average student assistant is not a trained armature winder and cannot get as much copper wire into slots of rotors or stators as could an experienced armature winder. On the other hand, the students do very well in making transformer coils and stator field coils using a winding machine. In order to minimize this difficulty, the tendency is to use relatively large slots which of course leads to irregularity in the torque curves. Commercial machines would probably use a large number of slots and would have a large collection of dies for punching small armature laminations. Burrs were quite a problem with the laminations when they were punched out until we found that we could mount a grind stone on our slow speed coil winding machine and grind them off without very much trouble.

To obtain the maximum amount of benefit in the way of instruction from use of this equipment it is very desirable that the dimensions of the magnetic circuit be known with a good degree of accuracy. With this end in view it is desirable to count the laminations used in the assembly of a rotor or other part of the magnetic circuit *before* the actual assembly. This precaution also applies to the construction of the transformers described in the first part of this report.

Once the laminations are assembled into the equipment it becomes almost impossible to count them accurately. What you have to do then is to have several people count them and strike an everage. Measurement of the actual thickness of a laminated structure and multiplication by an assumed stacking factor serves as a check but is not very accurate for actual computations, at least if only a few units of a certain kind are being built.

Friction undobtedly causes the most trouble encountered in the use of these torque demonstration devices, whether standard types of commercial motors are used or whether the devices described in this report are used.

There are, of course, certain experimental procedures for minimizing the effect of static friction in the torque readings, such as moving the rotor in opposite directions and taking the average of the two readings, etc. Special care should be taken that there are no bolts or mechanical parts rubbing together unnecessarily to cause friction. It is very easy to overlook some of these items without a careful examination during assembly.

It should be possible to modify the torque demonstration units which were constructed, so as to obtain more torque than was obtained. In any event, the torque obtained would be less than that obtained as a regular motor in which all of the windings are properly excited and in use. Laboratory torque tests are shown for a 3 hp six pole 60 cycle wound rotor induction motor in Figure 20. This test was made with one phase of the stator in series with two of the rotor terminals. Computations will show that the torque obtained from Figure 20 is only a fraction of the torque which would correspond to 3 hp at 1150 rpm. This of course is because for the 3 hp standard motor operation all the windings are in use and properly excited. We therefore cannot expect to get a torque corresponding to 10 hp at 3500 rpm for this particular equipment simply by using a 10 hp stator. We believe, however, that the torque developed in the prototype models would be considerably increased if a smaller air gap, attainable with different rotors, were used, We made the air gaps of all these torque demonstration units ⅛ inch in radial length because we wanted sufficient space to insert Hall effect wafers in the air gap between rotor and stator. This was a larger air gap than we really needed for purposes of mechanical clearance. It reduced the flux per pole and hence the amount of torque developed for a given excitation. On the other hand, it turned out that the ⅛" air gap was not large enough to insert a Hall effect wafer in the air gap with safety. As a result, the first experimental models which were built do not have as much torque as they should have and are still not suitable for inserting Hall effect wafers in the air gap to measure flux densities. The obvious remedy for this condition is to have two sets of rotors. One set of rotors will have a small air gap for use whenever one wants to demonstrate torque development. The other set of rotors will give a considerably larger air gap of sufficient size to insert a Hall effect wafer between rotor and stator for measuring flux densities.

The use of a salient pole stator with a wound rotor to demonstrate reluctance torque by exciting the rotor has very little to recommend it as compared to the use of a salient pole rotor used in conjunction with a wound stator. Both arrangements can be used to demonstrate reluctance torque but the wound stator can usually supply more ampere turns across the air gap than can the cylindrical rotor. On the other hand, we expect the salient pole stator construction to be of considerable use when it is dseired to take flux density curves in the air gap with a Hall effect wafer. For this situation the air gap will be large and we can obtain plenty of ampere turns acting across the air gap from the design of salient pole stator employed.

In completing our remarks regarding the torque demonstration units that were built, we would say that they are much more expensive and difficult to build than the transformers described in the first part of this report. At the same time, we believe that they are better suited for laboratory instructional purposes to demonstrate reluctance torque, excitation torque, and various combinations thereof, than are commercial electric motors. Although difficulties were encountered with the first prototype units built, we obtained considerably better results in the measurements of reluctance torque with these machines than we did with commercial machines. The prototype units can be used on either alternating current or direct current. We believe that the prototype units can be considerably improved in performance by a few minor modifications.

DEMONSTRATION OF FORCES ON A CURRENT CARRYING CONDUCTOR

One of the things which we had hoped to do on this project was to build equipment for demonstrating the force on a current carrying conductor in a magnetic field as given by the equation F = BLI.

As is well known in electrical machinery theory, if a current carrying conductor is imbedded in an iron slot, the flux density around the conductor will be less, the forces developed by the current carrying conductor itself will be less, but the total force on the system for a given flux per pole will be the same whether the conductor is imbedded in the iron slot or on the surface of an iron cylinder in air. The difference in force of course is the force exerted by the iron itself. What we had hoped to do was to build a prototype unit which would measure the forces on the conductor and on the surrounding iron separately.

There is no particular difficulty in measuring the force on a current carrying conductor in the air gap of an electro-magnet. The Ealing Corporation, Cambridge, Massachusetts, has developed relatively inexpensive equipment for demonstrating the force on a current carrying conductor in a magnetic field.

What we had hoped to do was to build equipment which would measure quantitatively the effect of current flowing through a straight conductor in a magnetic field in the air gap of an electro-magnet. Iron members would then be introduced into the air gap and an arrangement provided whereby the force on the conductor and the force on the iron member introduced into the air gap could be measured separately and with quantitative results. It develops that this is not such an easy thing to do, as the action of an irregular shaped piece of iron between the poles of a large electro-magnet is somewhat unpredictable. Other technical obstacles also exist.

We have constructed an electro-magnet which we hope can be used for this purpose and we have worked out a tentative design of equipment, using strain gauges, for measuring the force on the iron and the current carrying conductor separately. We are not in a position to say just how this scheme would work out since we have not actually constructed the fixtures for positioning the iron and current carrying conductors. Moreover, we have not constructed the circuitry for incorporating the strain-gauges into a display scheme. At this juncture, it seems that we have not made much of a start on this portion of the project. Our efforts are continuing and if we are able to complete our design and test the equipment for demonstrating forces on current carrying conductors, we will report upon it elsewhere.

CONCLUSION

In this report we have given an account of the work performed to develop electrical engineering laboratory equipment with support from NSF Grant Number 22948. Various prototype models were constructed, given engineering tests, and tried out in our electrical engineering laboratory classes. As is usual in engineering development work, the first prototype models revealed disadvantages which can be corrected in future designs.

The most successful project was the development of a single phase single core laboratory transformer and a 3 core laboratory transformer for the study of transformers and magnetic circuits in the electrical engineering laboratories. This particular project was successful in every respect and we believe the equipment can be constructed by the type of shop found in most electrical engineering departments.

Prototype equipments were built for demonstrating the development of torque in rotating machines. This includes a demonstration of both reluctance torque and excitation torque. This equipment was successful in that considerably better results were obtained in the classroom than had been obtained previously using commercial equipment. However, the equipment is more difficult to build and more expensive than the transformer units mentioned. Additional engineering work also needs to be done to improve the performance of the prototype torque demonstration models.

The time available for work on this project did not permit us to complete the work of mounting Hall effect wafer units in the air gap for measuring air gap flux densities or to construct equipment for demonstrating the separate forces on a current carrying conductor and on the iron surrounding that conductor.

In the course of this work it became obvious that electronics measuring equipment is going to be used more and more in the electrical machinery laboratory. The vacuum tube voltmeter and the cathode ray oscilloscope have been found to be very useful instruments to use in addition to the usual voltmeters, ammeters, and wattmeters, etc., commonly used in the electric machine laboratory. We believe that this trend will continue.

John F. Lamb
James R. Tudor
Project Directors

Electrical Engineering Department
University of Missouri
Columbia, Missouri

March, 1965

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Laboratory Mechanics

Eldon Breedlove, Instrument maker
Leon Richardson, Technician

Graduate Students

Henry M. Fendrich
John C. Huber
Aldolfo G. Lopez
Steve L. Wyrostek

The above graduate students were of considerable assistance in working out various design problems encountered, making many of the detailed electrical design computations, testing completed prototype units, and general trouble shooting.

Undergraduate Students Assistants

M. H. Acevedo
B. N. Anadu
Roger Allbritton
Larry J. Augustine
John L. Ingverson
George H. McCright, Jr.
James L. Poe

With the exception G. H. McCright, Jr., the above students did much of the actual construction work on this project and also some of the test work.

Particular credit should go to Eldon Breedlove for supervising the work of the undergraduate students in the shop and for helping us out in many tough construction problems.

Roger Allbritton and Larry Augustine were particularly outstanding in their ability to construct new and unfamiliar equipment in the shop.

George H. McCright, Jr. performed an outstanding job in handling all the drafting work done on this project. He did much of the actual detailed mechanical design required.

John F. Lamb
James R. Tudor
Project Directors

APPENDIX - COST ESTIMATE

Most of the construction work on this project was performed by part time undergraduate student assistants working under the supervision of the department labratory mechanic. The laboratory mechanic did all of the lathe work and the arc welding needed.

The range of mechanical abilities present in student assistants varies widely from one individual to the other. Usually several different experimental devices were under construction simultaneously, and no record of specific time worked on each device was taken. It is therefore, impractical to give any meaningful estimates of shop time in man-hours required to construct any of the specific devices described in this report.

The cost of construction labor is greatly affected by the availibility of certain shop tools. Although coils of magnet wire can be wound on an ordinary lathe, a low speed coil winding machine with a turn counter is time saving and can be operated by relativly unskilled student assistants. The coil winding machine can also be used to de-burr iron laminations by mounting a grinding wheel on its head stock and operating at low speed. Until this was done, the removal of burrs from punched iron laminations was quite difficult and time consuming.

A hand-operated metal shear machine is essential for shearing the silicon steel laminations. Also a metal punch for punching out slots in the rotor laminations is necessary. Slot dies for use with this punch cost about $20 to $40 apiece and wear out fairly rapidly in punching silicon steel laminations.

If a baking enamel is used for impregnating the wound electrical coils, an electric oven is necessary. This oven can also be used to cure the adhesive used to hold the iron laminations together. The curing for these operations require several hours at about 300°F. We used a 230 volt, 4kw, electric oven with inside dimensions of 25" x 20" x 20" and an automatic temperature control which could be adjusted over a working range from 160° F to 600°F. If an oven is not available, an air drying insulating varnish can be used on the electrical coils, and the iron laminations can be held together by insulated bolts instead of by the use of adhesive.

Tables A-I, A-II, A-III, A-IV, and A-V show the estimated material costs for the various devices constructed on this project. The amounts shown do not make any provisions for materials lost in scrap.

Too much reliance should not be placed on the cost figures shown in these tables as the actual costs are subjected to considerable variations.

The chief variable is the fact that suppliers' prices are considerably lower if large quantities are purchased. Silicon steel, magnet wire, casters, brush holders, carbon brushes, and many other things can be obtained much cheaper in large quantities. In many cases, a minimum charge per order exists. Also some suppliers will supply only a certain minimum quantity on any one order. For example, we actually used only about a 20 inch length of round copper bus pipe on our entire project. However, the minimum amount we could obtain on one order from the supplier was a length of seven feet.

The tables show the costs of materials if purchased in the quantities actually ordered for this project.

Local conditions also affect the cost of materials. In our laboratory we use 100 ampere female plugs in making electrical connections. We therefore used the corresponding 100 amp receptacles on the terminal connections to external equipment. These cost about $2.50 each if bought in large quantities. Other laboratories would use different types of line receptacles on the terminal boards in order to be compatible with their existing equipment.

TABLE A-I

Estimated material costs for single phase, single core, six coil laboratory transformer, Figures 2, 3, 4, and 5.

40 Pounds of M-15 grade, non-oriented, silicon steel sheets	$9.25
52 Pounds of AWG #14 round, double film, copper magnet wire	37.00
2 Square feet of 1/8" thick NEMA grade GPO-1 sheet laminate	2.20
1 roll (72 yds.) of 2" wide x 5 mil thick epoxy treated glass tape	3.00
1.5 Quarts of baking type insulating varnish	1.80
1.5 Pints of adhesive for iron laminations	2.30
4.5 Square feet of 1/8" aluminum sheet for terminal boards	6.30
45 Pounds of structural steel for frame	5.40
4 Swivel type casters	16.00
96 Insulated banana jacks for coil terminals	21.10
4 One-hundred ampere receptacles for terminal board	10.00
Miscellaneous items such as lead wire, insulating sleeving, wire for search coils, wood mounting parts, bolts, etc.	13.00
Total estimated cost of materials for one unit	$127.35

TABLE A-II

Estimated material costs for three core, 12 coil, laboratory transformer, Figures 10, 11, 12, 13, and 14.

56.8	Pounds of M-15 grade, #29 gage, non-oriented silicon steel sheets	$13.10
85.4	Pounds of AWG #14, round, heavy film, copper magnet wire	56.40
3.5	Square feet of 1/8" thick NEMA grade GPO-1 sheet laminate	3.85
2	Rolls (72 yds. each) of 2" wide by 5 mil thick epoxy treated glass tape	6.00
3	Quarts of baking type insulating varnish	3.60
2.25	Pints of adhesive for iron laminations	3.38
6.5	Square feet of 1/8" thick aluminum sheet for terminals boards	9.10
46	Pounds of structural steel for frame	5.52
4	Swivel type casters	16.00
140	Insulated banana jacks for coil terminals	30.80
6	One-hundred ampere receptacles for terminal board	15.00
	Miscellaneous items such as lead wire, insulating sleeving, wood mounting parts, bolts, etc.	16.00
	Total estimated cost of materials for one unit	$178.75

TABLE A-III

Estimated material costs for 2 phase, 2 pole wound stator units. Rotors not included. Figures 22, 23, 24, 25, 26, and 27.

The materials cost of the mounting frame, terminal boards, casters, wiring, bearings, etc. was the same for both units. The materials costs per single unit for these items is as follows:

73	Pounds of structural steel	$ 8.75
4	brushholders	25.20
4	carbon brushes	5.20
2	Sq. ft. of 1/8" thick aluminum sheet	2.80
4	Swivel type casters	16.00
16	Insulated banana jacks	3.52
8	One-hundred ampere receptacles	20.00
	Miscellaneous items such as bolts, lead wire, insulating sleeving, ball thrust bearing, guide bearing material, etc.	15.00
	A. Total material cost for one unit excluding wound stator	96.47
	B. Cost of Unmounted wound stator (See Figure 22)	
	B_1 7.5 hp, 2 phase, 2 pole, 220-440 volt wound stator	60.00
	B_2 10 hp, 2 phase, 2 pole, 220-440 volt wound stator	80.00

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Total approximate materials cost for one assembled unit.		(A + B)
Model A - 7.5	($A+B_1$)	$156.47
Model B - 10	($A+B_2$)	176.47

TABLE A-IV

Estimated material costs for salient pole stator units. Figures 32 to 40 inclusive. Rotors not included.

Material Description	Model A-7.5		Model B-10	
	Quantity	Cost	Quantity	Cost
M-15 grade, non-oriented silicon steel sheets. #29 gage	201 lbs.	$46.23	229 lbs.	$52.67
Heavy film, round magnet wire	38 lbs. of #14 wire	26.70	48 lbs. of #12 wire	32.30
Insulating varnish	2.6 quarts	3.12	2.6 quarts	3.12
Adhesive for iron laminations	5 quarts	15.00	5 quarts	15.00
Structural steel	82.3 lbs.	9.90	106.3 lbs.	12.83
Brushholders	4	25.20	4	25.20
Brushes	4	5.20	4	5.20
Swivel type casters	4	16.00	4	16.00
1/8" thick aluminum sheet	3.3 Sq. Ft.	4.62	3.3 Sq. Ft.	4.62
Insulated banana jacks	52	11.44	52	11.44
100 ampere receptacles	6	15.00	6	15.00
Miscellaneous items such as bolts, lead wire, insulation, bearings, etc.,		19.00		19.00
	Total estimated materials cost	$197.41	Total estimated materials cost	$212.38

TABLE A-V

Estimated material costs for the rotors. Figures 29, 30, and 31.

Two salient pole rotors and two cylindrical rotors were constructed; for practical purposes the material costs for these rotors were all about the same. In fact the shafts and slip rings were interchangeable.

A. Slip ring assembly. Four slip rings.

6.75" of 1.25" OD x 1" I. D. steel tube	$0.80
Four 3/4" wide rings cut from 4.00 inch O. D., 0.30 inch thick of Anaconda extra heavy copper bus pipe, 3 1/2" SPS.	3.00
Fiberboard washers and tubing, lead wire, 1/8" steel rods, and other miscellaneous items.	5.00
3 pounds of epoxy resin plus hardener.	4.50
Total estimated material cost for one slip ring assembly.	$13.30

Quotations for completely assembled slip rings (for only 3 rings) were obtained from commercial suppliers and ranged from $45 to $60 apiece in small quantities.

B. Rotor Units

15	Pounds of M-15 grade, silicon steel sheets	$3.45
10	Pounds of magnet wire.	6.50
7	Pounds of steel shafting	1.25
0.5	Pints of adhesive for laminations,	0.75
	Insulation, including baking varnish, slot insulation and ground insulation.	2.50
	One slip ring assembly as described in Part A above.	13.30
Total estimated material cost (average) per rotor		$27.75