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The experimental determination of the performance of a capacitor-excited induction generator with an inductive reactance in series with the load

Goode, Richard William; Hoffmann, Henry Acker; Searle, Willard Franklyn

Massachusetts Institute of Technology

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THE EXPERIMENTAL DETERMINATION OF THE  
PERFORMANCE OF A CAPACITOR-EXCITED  
INDUCTION GENERATOR WITH AN INDUCTIVE  
REACTANCE IN SERIES WITH THE LOAD

---

RICHARD WILLIAM GOODE  
HENRY ACKER HOFFMAN  
WILLARD FRANKLYN SEARLE, JR.

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THE EXPERIMENTAL DETERMINATION OF THE PERFORMANCE OF A  
CAPACITOR-EXCITED INDUCTION GENERATOR WITH AN INDUCTIVE REACTANCE  
IN SERIES WITH THE LOAD

by

Richard William Goode, Lieutenant, U. S. Coast Guard  
B. S., U. S. Coast Guard Academy, 1944

Henry Acker Hoffmann, Lieutenant Junior Grade, U. S. Navy  
B. S., U. S. Naval Academy, 1947

Willard Franklyn Searle, Jr., Lieutenant, U. S. Navy  
B. S., U. S. Naval Academy, 1945

Submitted in Partial Fulfillment  
of the Requirements for the  
Degree of Naval Engineer  
from the  
Massachusetts Institute of Technology  
1952





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ABSTRACT

Recent developments in the field of power capacitors have lead to renewed activity in theoretical and experimental investigations of the self-excited induction generator with particular consideration being given to high-frequency applications. The generating unit using shunt capacitors to provide excitation current has not presented satisfactory voltage regulation characteristics. As the load power factor becomes more lagging, the voltage regulation becomes increasingly poor.

In an attempt to improve the voltage regulation the induction generator has been investigated with compensation attained by the use of additional capacitance in series with the load. This operating technique causes possible loss of excitation over a certain range of power demand at lagging power factors. Theoretical studies indicate that, if compensation were accomplished by using an inductive, rather than capacitive, reactance in series with the load, generation could be maintained continuously for all load demands at any lagging power factor.

Experimentation in this thesis work verifies these facts. Further, voltage regulation can be improved by either decreasing series inductance or increasing shunt capacitance. Generation will be continuous from no load to maximum power output.

No excessive currents or voltages occur in the generating equipment or in the line as a result of transients following faults. Frequency variations, however exist after sudden load changes. This problem, as well as that of voltage regulation, may well be handled by the application of automatic control equipment.

17118  
Thesis Supervisor: Alexander Kusko  
Title: Associate Professor of Electrical Engineering  
17118

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DEPARTMENT OF CHEMISTRY  
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LETTER

Dear Sir,  
I have the pleasure to inform you that your letter of the 10th has been received and that the work is being carried out as rapidly as possible. I am sure that you will be satisfied with the results.

I am sure that you will be satisfied with the results. I am sure that you will be satisfied with the results. I am sure that you will be satisfied with the results.

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811/1

27  
Cambridge, Massachusetts  
May 16, 1952

Secretary of the Faculty  
Massachusetts Institute of Technology  
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "The Experimental Determination of the Performance of a Capacitor-Excited Induction Generator with an Inductive Reactance in Series with the Load".

Respectfully,

---

Richard W. Goode  
Lieutenant, U.S.C.G.

---

Henry A. Hoffmann  
Lieutenant j.g., U.S.N.

---

Willard F. Searle, Jr.  
Lieutenant, U.S.N.

Washington, D.C.  
July 10, 1952

Secretary of the Society  
Mathematical Institute of Technology  
Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the degree  
of level engineer, we shall furnish a thesis on  
the "The Statistical Treatment of the Data  
from a Computer-Controlled Injection Control  
with an Automatic Control in Diesel Engine Test".

Sincerely,

---

Richard W. Lusk  
Lieutenant, U.S.N.

---

Henry A. Williams  
Lieutenant J.G., U.S.N.

---

William F. Lewis, Jr.  
Lieutenant, U.S.N.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Professor Alexander Kusko of M. I. T. and to Dr. James B. Friauf of the Bureau of Ships, Department of the Navy, for their advice and encouragement.

PROPOSAL

The authors wish to express their appreciation  
to Professor Alexander Kohn of A. I. T. and Dr.  
Dr. James H. Smith of the Bureau of Birds, Depart-  
ment of the Navy, for their advice and encouragement.

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## I. INTRODUCTION

The advantages of the induction generator, stemming from the squirrel-cage rotor construction, are known. Power companies have installed induction generators as supplementary power sources. In these installations, magnetizing current is supplied by the synchronous machinery of the system to which it is connected. The inherent ruggedness, low maintenance, high speed possibilities, and low cost of construction of an induction generator could be enjoyed to a greater extent if the machine could operate satisfactorily as an independent source. Independence can be accomplished by the use of static capacitors as a source of magnetizing current. However, experimental and theoretical analyses included in the literature lead to the conclusion that until satisfactory schemes of voltage regulation are developed, the induction generator will not be acceptable as an independent source of electrical power.

Moreover, if the induction generator is compensated with capacitance inserted in series in the line, power generation will be lost for certain lagging power factor loads. Inasmuch as improvement of the voltage regulation may be accomplished by some form of series compounding, it seems logical to investigate the effect of inductive reactance on power continuity. Examination of the theory reveals that if inductive reactance were used, voltage

The advantages of the induction generator, although  
 from the capital-cost point of view, are known.  
 Power companies have installed induction generators in  
 applications where surplus power is available. In these instances,  
 regulated current is supplied by the synchronous machine  
 of the system to which it is connected. The induction motor  
 runs, for instance, from a synchronous generator, and the  
 rate of contribution of an induction generator could be  
 varied to a certain extent by the induction generator  
 characteristics as an induction motor. Induction can  
 be recognized by the use of static compensators as a means  
 of regulating the power. However, conventional and direct-  
 field analysis indicates in the literature that the  
 induction motor will contribute to the system as a  
 generator and vice versa. The induction generator will  
 not be recognized as an independent source of electrical  
 power.

Moreover, if the induction generator is connected  
 with capacitors instead of inductors in the first place,  
 generation will be lost for certain loading power factor  
 levels. Inasmuch as improvement of the voltage regulation  
 may be accomplished by some form of series compensation,  
 it seems logical to investigate the effect of induction  
 reactance on power continuity. Examination of the theory  
 reveals that if induction reactance were used, voltage

compensation will result and power generation is assured for all lagging power factor loads.

The purpose of this thesis is to experimentally investigate the characteristics of a self-excited induction generator using an inductive reactance in series with the load. Steady state performance is observed for unity, leading, and lagging power factors and for variations in shunt capacitance and series inductance. Transient behavior is studied under the conditions of short circuits, suddenly applied loads, and suddenly removed loads.

operation will range and power generation is assumed  
for all leading power factor loads.

The purpose of this study is to experimentally in-  
vestigate the characteristics of a self-excited induction  
generator using an automatic procedure in order to find the  
load. Every time generator is started for any

loading, and leading power factors and for variation in  
short-circuit and power inductance. Transfer  
behavior is studied under the conditions of short circuits,  
excessively applied loads, and suddenly removed loads.

The study is divided into two parts. In the first part,  
the characteristics of a self-excited induction generator  
are studied under various loading conditions. The second part  
deals with the automatic procedure for starting and loading  
the generator. The results of the study are presented in  
the form of graphs and tables. The study is carried out  
using a computer program written in Fortran. The results  
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## II. PROCEDURE

Prior to conducting the experimental work, the performance of the induction generating unit was analyzed<sup>1\*</sup>. Values of capacitive and inductive reactance were estimated for use in conducting the experimental work. In the laboratory, the generator was operated at constant frequency. Combinations of resistors, capacitors, and inductors were used to provide the desired load magnitude and power factor. Load voltage and current, generated voltage and current, power factor, power input, and power generated were recorded to determine the steady state characteristics of the generating unit. The efficiency of the generator was determined for all operating conditions.

An oscillograph was used to record the voltage and current transients occurring under single- and three-phase short circuits, suddenly applied loads, and step unloading. These transients were observed at both the load and machine terminals.

A detailed discussion of this procedure appears in the Appendix. Included also is a brief review of the performance calculation technique employed.

---

\* Superscripts refer to references as listed in the Bibliography.

The above method for determining the maximum efficiency of the system is a function of the generator efficiency, the efficiency of the transformer, the efficiency of the induction motor, and the efficiency of the synchronous motor. In this paper, the efficiency of the generator is assumed to be 90%, the efficiency of the transformer is assumed to be 95%, and the efficiency of the induction motor is assumed to be 85%. The efficiency of the synchronous motor is assumed to be 90%. The efficiency of the system is assumed to be 90%. The efficiency of the system is assumed to be 90%. The efficiency of the system is assumed to be 90%. The efficiency of the system is assumed to be 90%.

The above method for determining the maximum efficiency of the system is a function of the generator efficiency, the efficiency of the transformer, the efficiency of the induction motor, and the efficiency of the synchronous motor. In this paper, the efficiency of the generator is assumed to be 90%, the efficiency of the transformer is assumed to be 95%, and the efficiency of the induction motor is assumed to be 85%. The efficiency of the synchronous motor is assumed to be 90%. The efficiency of the system is assumed to be 90%. The efficiency of the system is assumed to be 90%. The efficiency of the system is assumed to be 90%.

A detailed discussion of this procedure appears in the Appendix. Included also is a table giving the performance calculation technique employed.

---

\* Efficiency is based on the assumption of 90% efficiency.

### III. RESULTS AND DISCUSSION OF RESULTS

#### A. Steady State Characteristics

The analytical determination of the performance of an induction machine when driven above synchronous speed has been covered by Dr. Friauf<sup>1</sup> and verified by Swift<sup>2</sup> for both simple capacitor-excitation and for capacitor-excitation with capacitance compounding. Estes and Hussong<sup>3</sup> extended this work to parallel operation but without compounding. In all three of the above, it was noted that for certain lagging power factor loads the excitation of the generator, and hence its voltage, was lost while the power was building up; and further, that this condition became more severe as the lag angle increased. (This phenomena is explained in the Details of Procedure in the Appendix.)

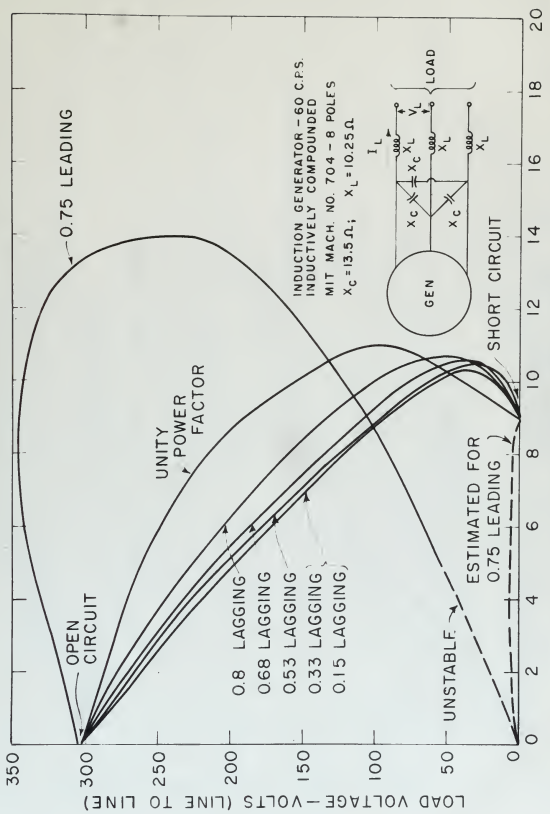
In order to verify the anticipated results that there would be no lagging power factor excitation discontinuity for an inductively compounded generator, values of  $X_C$  and  $X_L$  were chosen, using the method of Friauf<sup>1</sup> as explained in the Appendix, to give a fairly high value of open-circuit voltage and a value of short circuit reactance only slightly below the excitation-limiting condition. Thus continuous excitation for the unity power factor condition was assured. A value of 13.5 ohms for  $X_C$  and 10.25 for  $X_L$  was used for the family of curves shown in Figures 1, 2 and 3.



4. The Physical Interpretation

The physical interpretation of the results of an  
 inductive machine with three rotor windings when the  
 been shown by Dr. Tolstoy<sup>1</sup> and verified by other  
 both steady and alternating and the corresponding  
 lines with constant conductivity. These are usually  
 extended this work to parallel resonance but without con-  
 sidering. In all cases of the above, it was taken that  
 for certain loading power factor leads the variation of  
 the generator, and hence the voltage, was less than the  
 power was increasing up and further, load was increasing  
 power rate covers as the load varies. (This  
 phenomenon is explained in the theory of resonance in  
 the Appendix.)

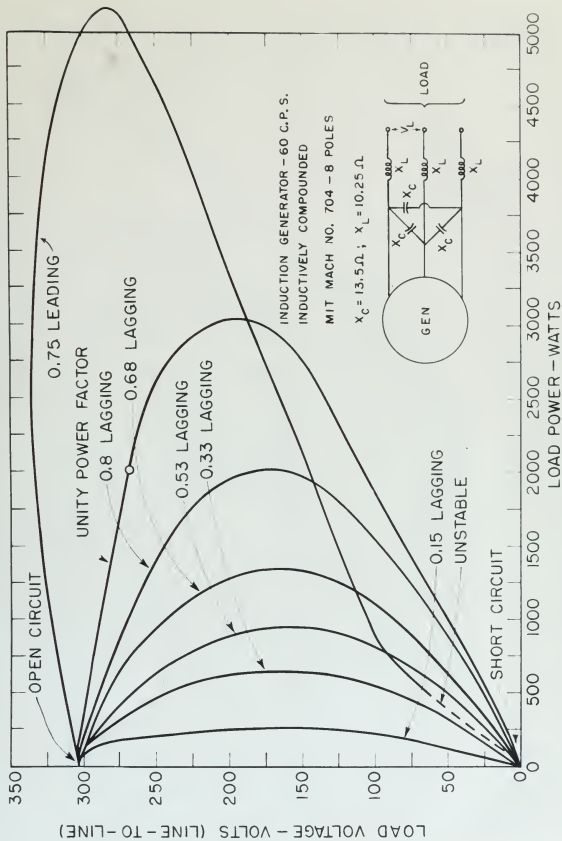
In order to verify the mentioned results that there  
 would be no lagging power factor condition characteristic  
 for an inductively compensated generator, values of  $X_L$  and  
 $X_C$  were chosen, using the method of Tolstoy<sup>1</sup> as explained  
 in the Appendix, so that a fairly high value of over-voltage  
 voltage and a value of reactive power was obtained with slightly  
 below the excitation-limiting condition. The following  
 excitation for the voltage power factor condition was chosen.  
 A value of 1.35 times the  $X_L$  and 0.75 for  $X_C$  was used for  
 the family of curves shown in figures 1, 2 and 3.



LOAD CURRENT AMPERES - LINE CURRENT TO LOAD  
LOAD VOLTAGE VS. LOAD CURRENT FOR VARIOUS LOAD POWER FACTORS

FIGURE 1





LOAD VOLTAGE VS LOAD POWER FOR VARIOUS LOAD POWER FACTORS  
FIGURE 2



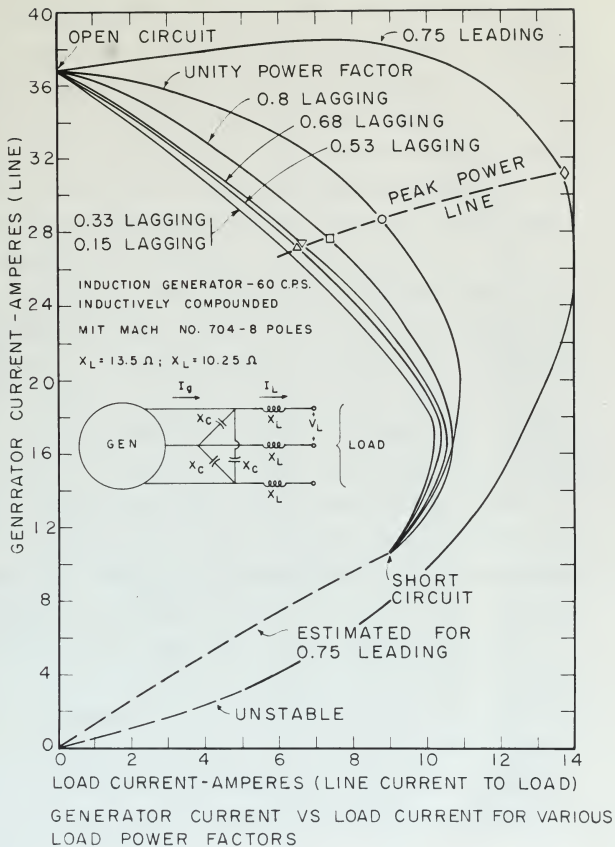


FIGURE 3



It is shown in these figures that a capacitor excited, inductively compounded induction generator will have continuous excitation from open circuit to short circuit, and hence continuous voltage and power characteristics, for all lagging load power factors, provided of course that the excitation is continuous at unity power factor. It is further shown in Figures 1, 2, and 3 that for leading power factors a point may be reached at which the magnetizing impedance is insufficient to give excitation current, and consequently the voltage and power will collapse. Note that in Figures 1 and 3 the leading power factor curve is discontinuous at the origin. This is the condition of no excitation. The theory leads to the fact that if the parameters are such as to permit a sustained short circuit, then generation should reoccur at some lower value of load impedance. It was found that the generator was very unstable in the region approaching loss of excitation and tended to drift toward no excitation at load voltages of about 60. It was also impossible to obtain re-excitation after passing continuously through the region of no excitation. The same condition was obtained, however, by overspeeding the generator, exciting at a higher frequency and hence a value of  $X_c$  below critical (see magnetizing curve, Figure A-3) and then slowing to 60 c.p.s. On Figures 1 and 3 the path of the curve for leading power factor between the point of re-excitation and short circuit is estimated and shown dotted.



It is shown in these figures that a capacitor excited, inductively connected induction generator will have continuous excitation from some distance to short circuit, and hence continuous voltage and power characteristics, for all leading load power factors, provided no current flows through the generator is continuous at unity power factor. It is further shown in figures 1, 2 and 3 that the leading power factor a point may be reached at which the maximum impedance is insufficient to give excitation current, and consequently the voltage and power will collapse. Note that in figures 1 and 2 the leading power factor curve is discontinuous at the origin. This is the condition of no excitation. The theory leads to the fact that at the point where the curve is to become a sustained lead circuit, then generation should increase as some lower value of total impedance. It was found that the generator was very unstable in the region approaching zero of excitation and tended to drift toward an excitation in lead voltage of about 50%. It was also impossible to obtain re-excitation after passing continuously through the origin to an excitation. The same condition was obtained, however, by reversing the generator, excited at a slight overvoltage and under a value of  $\phi$  below critical (see paragraph 4, figures 4-5) and then allowing to go a.r.s. In figures 1 and 2 the part of the curve for leading power factor between the point of re-excitation and short circuit is believed not shown.

It is most important to note here that the loss of excitation occurred well after the power peak and not during the power build-up as was the case described by Swift<sup>2</sup> for the capacitance-compounded generator. This is, of course, because the critical value of magnetizing reactance as seen by the machine terminals themselves (inside  $X_C$  and  $X_L$ ) does not drop to the critical value until well after the peak conditions. This is explained in detail in the Appendix.

Figures 1 and 2 indicate the fact that the voltage regulation becomes very poor and the peak power available drops off sharply as the power factor loads become increasingly lagging.

Figure 3 brings out the fact that for unity or lagging power factors the highest value of the generator current,  $I_G$ , occurs at the no load condition. (It thus came as no surprise that an easy way to cool off the test machine was to load it down.) It was for this reason that no attempt was made at interpreting the results as per-unit values. Conventional rating methods do not apply to a generator of this type inasmuch as the ratio of the KVA rating of the machine proper to the corresponding KVA rating of the output terminals is so large. This is due to the unavoidable fact that a large part of the generator current must go through  $X_C$ , reducing  $I_L$  relative to  $I_G$ , notwithstanding the phase angle consideration.

It is most important to note that the loss of  
excitation associated with the power loss and not  
during the power build-up as was the case described in  
Table 1 for the conventional compressor operation. This  
is, of course, because the critical value of excitation  
remains as seen by the machine remains constant  
(inside  $X_c$  and  $R_c$ ) and not due to the critical value  
which will vary with the excitation. This is explained  
in detail in the Appendix.

Figure 1 and 2 illustrate the fact that the critical  
excitation remains very high and the loss of excitation  
does not change as the power factor leads become lagging-  
ingly leading.

Figure 3 shows that the fact that the loss of excitation  
remains constant the highest value of the excitation current.  
It occurs at the same location. It is not seen as an  
excitation that is very low in fact all the time because the  
to load it down. It was for this reason that the system  
was made as interesting the results as previously shown.

Conventional field method we can apply to a variation of  
this type because as the ratio of the  $X_c$  ratio of the  
machine proper to the corresponding  $X_c$  ratio of the system  
remains is so large. This is due to the relationship that  
that a large part of the generator output goes as though  
to the generator  $X_c$  relative to  $X_c$  corresponding to the  
single connection.

A cross curve of peak power is shown in Figure 3. This has no significance other than perhaps predicting the load current and the  $I_L$  to  $I_G$  ratio at peak power for some other power factors. It is worthy of note that as the power factor increases from highly lagging to unity to leading, the ratio of  $I_L$  to  $I_G$  increases. This fact of itself would lead us to the conclusion that since more of the rated current of the generator proper is getting to the load, the machine is operating more efficiently at the higher power factors. Table I shows the approximate value of the efficiency of each run at the maximum power point. The values were arrived at by subtracting the d-c drive motor losses from the d-c input power and calculating the induction generator efficiency by using the shaft input power and wattmeter readings at the load. No account was taken of meter losses or the losses occurring in the variac.

TABLE I

Efficiency at Maximum Power Condition  
for Various Load Power Factors

$X_c = 13.5$	$X_L = 10.25$
<u>Power Factor</u>	<u>Efficiency</u>
0.15 lag	16.6
0.33	33.6
0.53	40.5
0.68	48.5
0.80	56.5
1.00 unity	63.6
0.75 lead	68.0

A more exact value is given in Table I.

For the calculations the data were corrected for the

power factor. It is known that the power factor

varies between 0.7 and 0.9. The power factor

was assumed to be 0.8. The data were corrected

for the power factor. The data were corrected

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Table I

Efficiency as a function of the power factor  
for the different power factors

Power factor	$\eta$
0.7	0.75
0.8	0.80
0.9	0.85
1.0	0.90
1.1	0.95
1.2	1.00

The voltage waveform for the generator unit was observed on an oscilloscope connected across the load during all the runs involved in Figure 1 and was found to be a pure sinusoid at all loadings. An example for 0.8 lagging power factor, at peak load is shown in Figure 4. This confirms for the compounded generator the results described by Estes and Hussong<sup>3</sup> for the uncompounded case. This may also be observed on the oscillograms of transient behavior included in the following section of this chapter.

In order to extend the results described above, a series of runs, all at unity power factor but with various  $X_L$  and  $X_C$ , have been plotted in Figures 5, 6, and 7. On each figure the center curve ( $X_L = 10.25$ ,  $X_C = 13.5$ ) is a duplication of the unity power factor curve of Figures 1, 2, and 3 respectively.

A decrease in the value of  $X_L$  relative to that of the first set of figures while holding  $X_C$  constant (same open-circuit voltage) gives perhaps the most important result obtained. Figures 5 and 6 show that for a given power output the voltage regulation from no load to a given load is considerably improved. For example, on Figure 5 at a 2.5 KW load, the improvement is from 18.5 percent to 8.9 percent. With an  $X_L$  of 3.7 the generator would undoubtedly be operated at a higher power where its regulation would drop off. It is seen in Figure 5 that the voltage characteristic is quite linear until about 3.5 KW. It is further noted that the peak power available is considerably greater as  $X_L$  is decreased.

The voltage waveform for the generator unit was observed on an oscilloscope connected across the load during all the runs involved in figure 1 and was found to be a pure sinusoid at all loadings. An example for 0.5 loading power factor, at zero load is shown in figure 4. This waveform for the compensated generator has been included in table 1. The frequency for the un-compensated case, 60 Hz, is also included in the table on the excitation of the generator. The following section of this report.

In order to obtain the voltage regulation curve, a series of runs were made at unity power factor and were shown in figure 5. On each figure the generator load is shown in terms of  $P$  and  $Q$ . On each figure the center curve is  $V_t = 1.0$ ,  $V_r = 1.0$  is a deviation of the unity power factor curve of figure 1, and is essentially a decrease in the value of  $V_t$  relative to that of the

first set of figures which shows the voltage regulation curve (solid voltage) and shows the deviation of the unity power output. Figure 6 and 7 show the voltage regulation curve for a given load in two slightly different cases. The example in figure 7 is a 0.5 power factor. The measurement is for 0.5 power factor and is shown in figure 8. The generator unit is connected to a load of 0.5 power factor and the results are shown in figure 9. It is seen in figure 9 that the voltage regulation is quite linear until about 0.5 power. It is noted that the best power available is consistently greater as  $V_t$  is decreased.

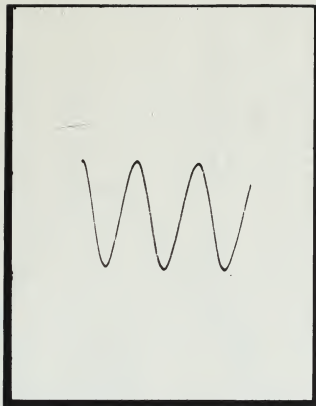
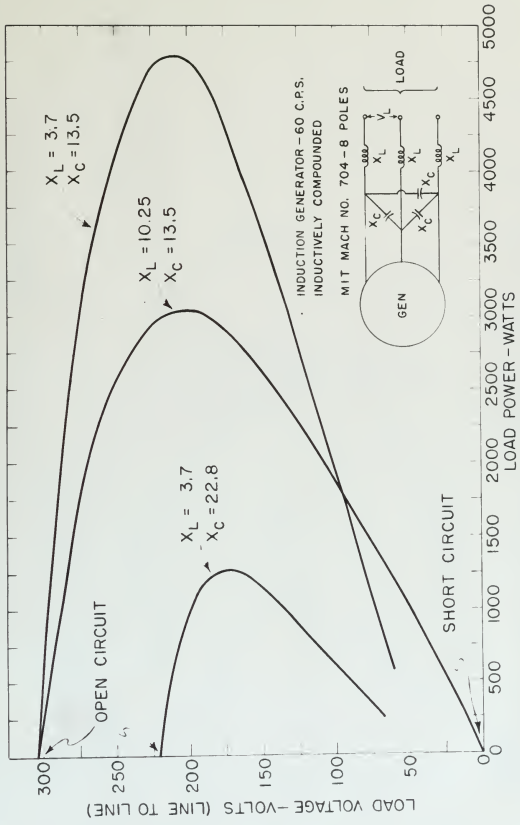


FIGURE 4  
Voltage Waveform



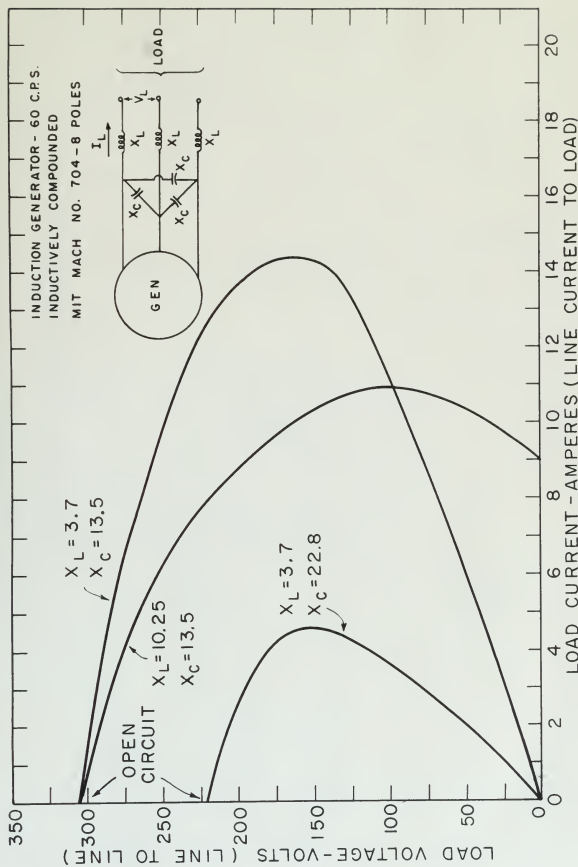




LOAD VOLTAGE VS LOAD POWER FOR UNITY LOAD POWER FACTOR WITH VARIOUS PARAMETERS

FIGURE 5





LOAD VOLTAGE VS LOAD CURRENT FOR UNITY LOAD POWER FACTOR WITH VARIOUS PARAMETERS

FIGURE 6



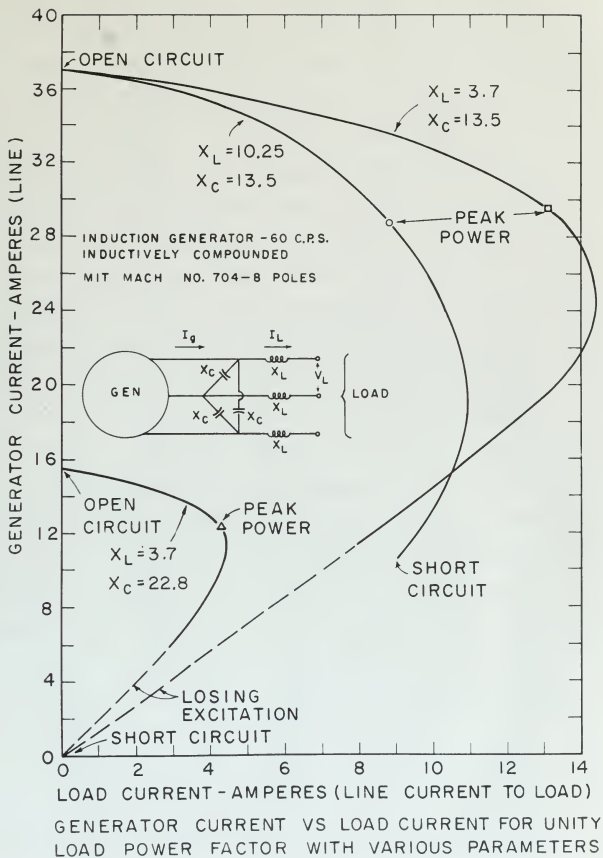


FIGURE 7



This all has been achieved by accepting a discontinuity in the excitation at the  $X_L = 3.7$  condition. The value of the short-circuit magnetizing reactance is such that it is above the critical value as shown on the magnetizing curve. Referring to Figure A-5(a), the short-circuit condition is below the limiting value of susceptance. As was noted previously, the point of initial loss of excitation is well beyond the peak power point, therefore, at a point where operation is unlikely. Also, and of equal importance, is the fact that lagging power factor loads would not cause loss of excitation at any earlier relative value of power.

Figure 7 shows that the two curves at  $X_L = 3.7$  have no sustained short-circuit current whereas the condition of the runs in Figures 1, 2, and 3 permits a sustained short-circuit of 9 amperes. This is borne out by the discussion in the preceding paragraph and will be mentioned at greater length in the section of this chapter on transients.

The results shown on Figure 7 indicate that for a given generator rating the ratio of load current to generator current is greater as the value of  $X_L$  is decreased. This of itself would again lead one to suspect better operating efficiency for the set with a lower  $X_L$ . At any rate, it would be expected that the generator-set rating (at the terminal beyond  $X_L$ ) would be closer to the required KVA rating of the machine proper. Note in Figure 7, as in Figure 3, that the rating of the machine needs to be much



This all has been covered by accepted a discontinuity in the excitation at  $\omega = 2.7$  oscillation. The value of the short-circuit impedance is such that it is shown the critical value is shown on the magnifying curve. Deflection of lines  $A-V_1$ , the short-circuit condition is below the limiting value at resonance. As was noted previously, the point of initial loss of excitation is well beyond the open power point, therefore, at a point where operation is unstable. This, and of equal importance, is the fact that power factor would not cause loss of excitation at any applied relative value of power.

Figure 7 shows that the two curves at  $\omega = 2.7$  have

no sustained short-circuit current because the condition

of the runs in Figures 1, 2, and 3 presents a sustained

short-circuit of 9 amperes. This is shown due to the

discussion in the preceding paragraph and will be mentioned

at greater length in the section of this chapter on transients.

The results shown on Figure 7 indicate that for a given

generator setting the ratio of load current to generator

current is greater as the value of  $\omega$  is decreased. This

of itself would explain why one is expected better operating

efficiency for the case with a lower  $\omega$ . At any rate, it

would be expected that the commutator setting for the

critical current  $\omega = 2.7$  would be lower in the respective

ratio of the machine power. Note in Figure 7, as in

Figure 3, that the setting of the machine needs to be such

higher than the rating of the generator set. The run at the lower value of  $X_L$  was indeed found to be more efficient as noted in Table II.

TABLE II

Efficiency at Maximum Power Conditions  
for Various Parameters with Unity Power Factors

<u>Parameters</u>		<u>Efficiency</u>
<u><math>X_L</math></u>	<u><math>X_C</math></u>	
10.25	13.5	63.6
3.7	13.5	68.3
3.7	22.8	65.8

The third curve on Figures 5, 6, and 7, namely,  $X_L = 3.7$  and  $X_C = 22.8$ , was run as a verification for the inductively compounded generator of the results predicted by Friauf<sup>1</sup> and checked experimentally by Swift<sup>2</sup>. The open circuit voltage is found to be much lower as the value of  $X_C$  approaches the critical  $X_C$  as shown on the magnetizing curve. As a consequence, the voltage regulation is very poor and the peak power available drops off rapidly. The set itself operates efficiently on an output-over-input basis. There is nonetheless a gross inefficiency in the use of the machine size involved.

To briefly summarize the important steady state results of the conditions investigated:

1. Continuous generation for all lagging power factors is assured if excitation is continuous for unity power factor.

higher than the value of the parameter  $\alpha$ . The sum of the lower value of  $\alpha$  and lower bound to be more realistic is noted in Table II.

TABLE II

Minimum of Positive Power Coefficient for Various Parameters and Power Coefficient

Parameter	Minimum of Positive Power Coefficient	
	$\alpha$	Power Coefficient
1.0	0.1	0.1
0.5	0.1	0.1
0.1	0.1	0.1

The initial curve as shown in Fig. 1 and Fig. 2, and  $\alpha = 0.1$  and  $K = 0.5$ , was used as a verification for the integrally computed constant of the steady condition of power.

and steady conditionally by itself. The same integral

value is found to be true for the value of  $\alpha$  approaches the value of  $\alpha$  found in the unsteady state. As a

consequence, the value of  $\alpha$  is very low for the steady state condition. The same result

applies equally on an air-cooled engine case. There is another aspect to be noted in the use of the method

also involved.

In order to maintain the accuracy of the steady state results at the condition investigated

1. Continuous operation for all engine cases

2. Factors in regard to excitation is constant

3. Use the only power factor.

2. In cases of leading or lagging power factor, where discontinuity of excitation exists, the discontinuity occurs after the peak power condition.
3. The voltage regulation and efficiency drop off rapidly for the more lagging power factor conditions.
4. Voltage generated is a pure sine wave.
5. Reduction of  $X_L$ , with  $X_C$  held constant, effectively improves voltage regulation and peak power.
6. KVA rating of the machine proper must be larger than the KVA rating at the terminals of the set and must be based on no-load (open circuit) conditions which are the most severe.

### B. Transient Studies

Sudden interruption of steady-state operating conditions in an electrical system may cause abnormal transient values of current and potential. Disastrous peak values of voltage surge or current in-rush may instantaneously exist even though safe, steady-state conditions prevail before and after the change. Also, the effects of abrupt faults, if not localized, may cause an entire system to become unstable. Generally, in an electrical system being supplied with induction generator power no intolerable transients occur, though the generator may become unstable and cease generation of voltage<sup>3</sup>.

1. In case of failure of leading power factor, there is possibility of excessive voltage, the alternator output after the load change condition.
2. The voltage regulator and automatic AVR will regulate the voltage output within limits.
3. Voltage generated is a sine wave.
4. Regulation of  $V_r$  with  $P$  will be constant. Effectively however voltage regulation will be poor.
5. AVR taking in the feedback power will be larger than the AVR output in the terminal of the set and will be based on no-load (open circuit) condition when the set is not loaded.

### 3. Parallel Operation

When frequency of alternator connected conditions in an electrical system are not constant, constant voltage of current and potential. Disturbance may occur in voltage or current is shown by parallel operation when two loads are, steady-state condition power factor and other the same. Also, the effects of output factor of the generator may lead to voltage regulation to become constant. Generally, in an electrical system being supplied with multiple generators power to individual branches must be from the generator may become unstable and cause generation of voltage.

a.) Three-Phase Short-Circuit - The transients at the load terminals and at the generator terminals resulting from a three-phase short-circuit are illustrated by the oscillograms of Figure 3. The value used for shunt capacitance in all transient studies was one which provided an open-circuit voltage of 305 volts. With the inductor selected, a reasonable power output of about 4.8 KW was obtained. The steady-state frequency before application of the short was 60 c.p.s. Thus, the initial portion of each trace may be referred to as a time scale.

Currents and voltages of only one phase are shown because balanced conditions existed. Figure 8-a shows current and voltage at the load terminals; Figure 8-b, the same at the generator terminals. The shorted load was at unity power factor.

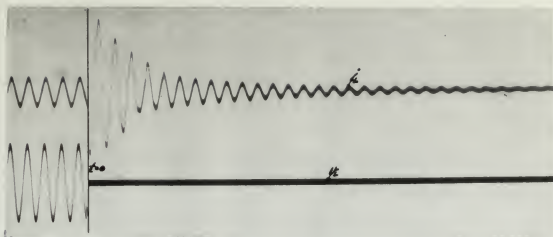
The load voltage,  $e_L$  of 8-a, obviously must change immediately to zero. There is an immediate peak of current,  $i_L$ , of about two and one-half times the initial current peaks. The current wave form is enclosed in an exponentially decreasing envelope. In approximately one-half second the short-circuit current is practically zero.

The time constant involved here is determined by the impedance of the equivalent circuit as seen looking back from the shorted terminals. Because four energy storage elements are involved, there will be four roots to the characteristic equation describing the impedance. No decaying direct-current component of line current can

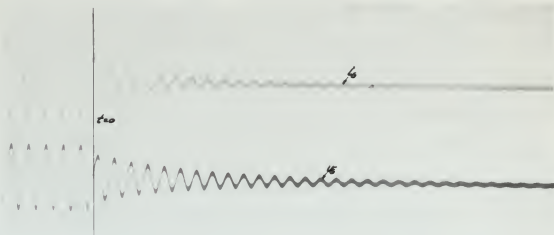
2.1. Open-Circuit Voltage - The terminals of the load terminals and at the generator terminals resulting two a three-phase open-circuit, are illustrated in the section of Figure 1. The values from the above experiment in all identical studies are which provided in open-circuit voltage of 200 volts. With the terminal voltage, a reasonable power factor of about 0.85 was obtained. The steady-state frequency before application of the load was 60 c.p.s. Thus, the initial voltage of each phase may be referred to as a line voltage.

Currents and voltages of each one phase are shown because balanced conditions existed. Figure 2-2 shows current and voltage at the load terminals. Figure 3-2 shows the load at the generator terminals. The measured load was at unity power factor.

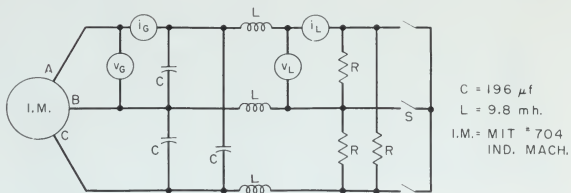
The load voltage of 200 volts, and the load current immediately to zero. There is an increase from 200 volts to 250 volts and possibly from the initial current. The current may have been increased in an experimentally decreasing voltage. In approximately 100-150 seconds the three-phase current is practically zero. The time constant involved here is determined by the inductance of the generator circuit as well as the reactance of the circuit. Because the energy stored in the generator is limited, the time constant in one characteristic quantity depending on the inductance, the frequency of the generator, and the load.



8-a. LINE TRANSIENTS



8-b. GENERATOR TRANSIENTS



TRANSIENTS FOLLOWING A THREE PHASE SHORT-CIRCUIT

FIGURE 8





be distinguished. For only about 0.1 seconds did the transitory line current have an effective value greater than that of the initial line current.

After the load was shorted out, the series inductance was effectively placed in parallel with the shunt capacitance. This combination appears to the induction machine as an inductive reactance of 5.1 ohms. Thus, excitation current cannot be supplied and the machine fails to generate.

Referring to Figure 8-b, it is seen that the stator current,  $i_g$ , and voltage,  $e_g$ , both go to zero without surging, and furthermore, that the response times are the same as that for the short circuit current in the line. It can be concluded that no damage to this generating unit will result because of a three-phase short-circuit. However, it is significant to note that unless a short-circuited branch can be removed from the system within a fraction of a second, all power service will be lost.

It should be pointed out that in the trace of machine current,  $i_g$ , there appears an initial surge of direct-current, followed by an exponential decay to zero. As a result, the entire exponential envelope of the sinusoidally-varying component is offset above the zero level. The offset phenomena depends upon the instant of transient introduction. The rate at which the offset decreases is considerably greater than the rate at which the envelope decays.

be distinguished. The only other (1) account of the  
 transition line current does not indicate any greater  
 than that of the initial line current.

After the lead was started and the series induction  
 was effectively closed in parallel with the short circuit.  
 This combination causes in the induction machine as an  
 inductive reaction of 0.1 amp. Total excitation current  
 cannot be supplied and the machine falls in reverse.  
 Reference to Figure 2-10, it is seen that the starting  
 current,  $I_s$ , and voltage,  $V_s$ , both as in part (b) of  
 winding, and furthermore, that the maximum lines are the  
 same as that for the short circuit current of the line.  
 It can be concluded that no damage is done by starting  
 unit will result because of a three-phase short-circuit.  
 However, it is extremely important to note that unless a three-  
 phase fault occurs and by reason of the system which a  
 function of a system, all power transfer will be lost.

It should be pointed out that in the event of starting  
 current,  $I_s$ , does not exceed the initial value of the  
 current, followed by an exponential decay as time goes  
 on. The initial momentary increase of the short-circuit  
 current component is only above the zero level. The effect  
 depends directly upon the length of transient inductance.  
 The rate at which the effect disappears is exponentially greater  
 than the rate at which the power decays.

b.) Single-Phase Short-Circuit - Of the two, the fault more commonly encountered is the single-phase, rather than a three-phase short-circuit. The transient effects of a single-phase short-circuit, as exhibited at the load terminals and machine terminals, are illustrated in the oscillograms of Figure 9-a and Figure 9-b, respectively. It was necessary to show traces for only phase B and either phase A or phase C. However, all three phases were trace-recorded and, obviously, the conditions of phase A were repeated in phase C. Actually, the pure resistance load was adjusted so that voltages in all three phases were closely balanced. Some unbalance is indicated in both oscillograms because the sensitive elements of the oscillograph did not permit fine adjustment of galvanometer sensitivity.

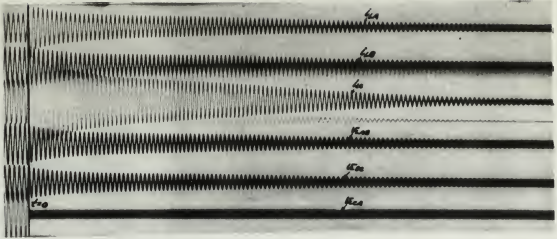
As in the previous case, with voltage,  $v_{Lca}$ , across the shorted phase going instantly to zero, the currents,  $i_{La}$  and  $i_{Lc}$ , in the shorted lines initially surge and thereafter exponentially decline to zero. Now, however, the rate of decay is nearly one-half that for the three-phase case. The maximum instantaneous current carried by the shorted lines is about twice the steady-state current peak. In the third line, the current never exceeds the steady state value, since neither end of the shorting cable is connected to phase B.

With voltage,  $v_{ca}$ , equal to zero, the instantaneous voltages,  $v_{ab}$ , and  $v_{bc}$ , must remain equal in magnitude and separated by a 180-degree phase angle. A "ghost"

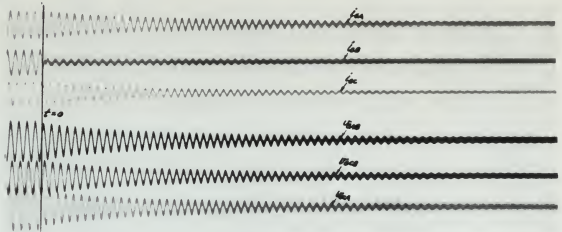
Fig. 10. Oscilloscope photograph of the signal. The signal is shown as a series of pulses. The horizontal axis is labeled  $t$  and the vertical axis is labeled  $V$ . The signal is shown as a series of pulses with a period of approximately 100 ns. The amplitude of the pulses is approximately 10 V. The signal is shown as a series of pulses with a period of approximately 100 ns. The amplitude of the pulses is approximately 10 V. The signal is shown as a series of pulses with a period of approximately 100 ns. The amplitude of the pulses is approximately 10 V.

As in the previous case, with voltage,  $V_{100}$ , either the shorter lines (with constant  $V_{100}$ ) or the longer lines ( $V_{100}$  and  $V_{100}$ ) at the shorter lines initially decay and the rate of decay is nearly one-half that for the longer lines. The maximum instantaneous current during the shorter lines is about twice the steady-state current. In the first line, the current never exceeds the steady state value, since the first part of the shorter cable is connected to ground.

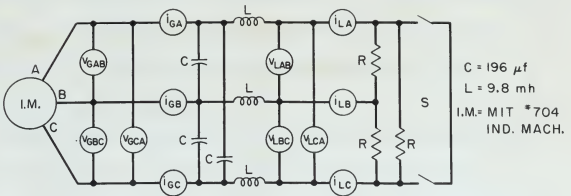
With voltage,  $V_{100}$  and  $V_{100}$  equal to zero, the instantaneous voltage,  $V_{100}$  and  $V_{100}$  that remain equal in magnitude and separated by a 180-degree phase angle. A typical



9-a LINE TRANSIENTS



9-b GENERATOR TRANSIENTS


 TRANSIENTS FOLLOWING A SINGLE PHASE SHORT-CIRCUIT  
 FIGURE 9



trace is apparent in the center of the upper oscillogram. This is attributed to a stray reflection from one of the potential - recording galvanometers.

The oscillogram of Figure 9-b shows transients at the machine terminals and is similar in pattern to the corresponding oscillogram of Figure 8-b for the three-phase short circuit. Two noteworthy differences are found, however. The first is manifested by the doubled time of decay, in agreement with conditions in the line. A possible explanation of this may be found in considering the transient voltages across the three shunt capacitors. With the three phase short circuit, these capacitors are each shunted through a series inductance. The voltage across the capacitors diminishes rapidly to zero. On the other hand, in the instance of single-phase shorting, only one capacitor is shunted through series inductance. It would be expected that the voltages across the other two capacitors would have a longer transient period. As long as these voltages are sustained, the induction machine will receive excitation current. It follows that power generation will not completely end as quickly as when all three phases are shorted.

A second major difference between the oscillograms of Figure 9-b and Figure 8-b is evident in the trace for current,  $i_{gb}$ , of the latter. It was pointed out previously that the line currents,  $i_{La}$  and  $i_{Lc}$ , momentarily surged to



trace is apparent in the center of the upper oscillogram. This is attributed to a heavy reflection from one of the potential - recording galvanometers.

The oscillogram of Figure 3-2 shows transients at the machine terminals and in similar in pattern to the corresponding oscillogram of Figure 3-1 for the three-phase short circuit. Two noteworthy differences are found, however. The first is manifested by the doubled time at decay, in agreement with conditions in the line. A possible explanation of this may be found in considering the transient voltages across the large shunt capacitors. With the three phase short circuit, these capacitors are each shunted through a series inductor. The voltage across the capacitors diminishes rapidly as usual. On the other hand, in the instance of single-phase shorting, only one capacitor is shunted through series inductance. It would be expected that the voltages across the other two capacitors would have a longer transient period. As long as these voltages are sustained, the induction machine will receive excitation current. It follows that power generation will not completely end as quickly as when all three phases are shorted.

A second major difference between the oscillograms of Figure 3-2 and Figure 3-1 is evident in the lower for current,  $i_{ob}$ , of the latter. It was pointed out previously that the line currents,  $i_{L1}$  and  $i_{L2}$ , momentarily ceased to

higher-than-normal values. To accommodate the current surges in the two phases, A and C, current is most readily drawn from phase B through the inter-connecting capacitors. This causes a sudden compensating drop in machine terminal current for the B-phase, as is shown in Figure 9-b.

Power is eventually lost because, as explained in the discussion of a three-phase short circuit, the reactance seen by the induction machine is not sufficiently capacitive to furnish the necessary excitation current.

c.) Induction Motor Starting - To simulate a varying load demand on this power generating unit, several trials were made wherein the system load was suddenly increased or decreased. This section investigates the transient effects of suddenly starting an induction motor. Oscillograms obtained include those of figures 10 and 11.

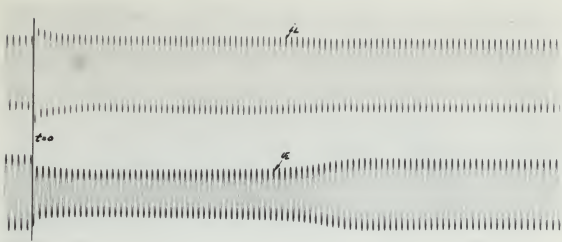
Figure 10 carried traces of line current,  $i_L$ , and voltage,  $v_L$ , and machine current,  $i_g$ , and voltage,  $v_g$ . For the trial illustrated, there was a prior balanced load on the generator of about 4.4 KW before starting the induction motor. The induction motor was started and run with a continuous shaft load equivalent to about 700 watts. From Figure 10-a it is seen that the line voltage initially dipped in agreement with comments elsewhere concerning voltage regulation. Once the inertia of the motor and connected load had been overcome, the line voltage increased to almost the original value. The line current during this

highest-thermal values. It is important to realize that  
in the case of a low C content, it may readily occur  
from phase 2 through the intermediate region.  
This stage is rather complicated and is usually omitted  
because of the danger, as is shown in Figure 4.  
There is eventually lost because, as explained in the  
discussion of a three-phase short circuit, the constant  
seen by the induction machine is not sufficiently constant  
due to the fact that the necessary excitation current

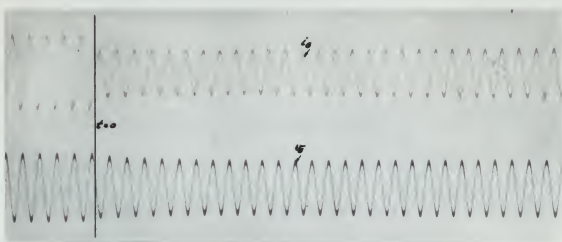
### 2.1 Induction Machine Starting - To obtain a starting

load current on the power generator side, several cases  
were made wherein the system load was suddenly increased  
or decreased. This section investigates the transient  
effects of suddenly changing an induction motor. Specific  
graphs obtained include cases of Figure 10 and 11.

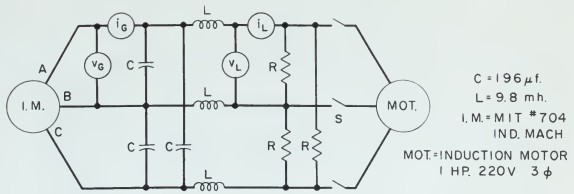
Figure 10 shows traces of the terminal voltage,  $V_t$ , and  
voltage,  $V_r$ , and machine current,  $I_m$ , and voltage,  $V_r$ .  
For the case illustrated, there was a three-phase fault  
on the generator of about 0.4 sec before starting the motor.  
The induction motor was started and ran 0.5 sec  
continuously with load equivalent to about 100% motor. Some  
figures show it is seen that the line voltage  $V_{LL}$  is  
dipped in accordance with constant air-gap voltage  
voltage regulation. Thus the fault on the motor and  
connected load had been removed, the line voltage increased  
to almost the original value. The line current  $I_m$  of this



10-a. LINE TRANSIENTS



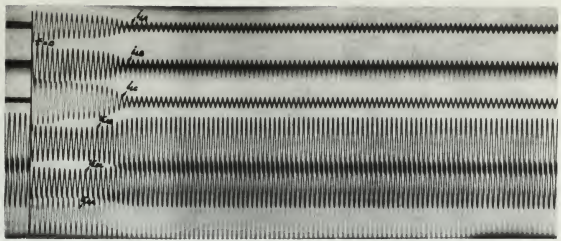
10-b. GENERATOR TRANSIENTS



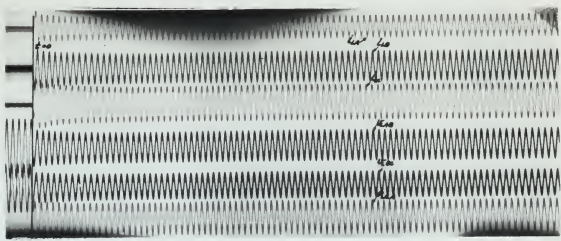
TRANSIENTS FOLLOWING INDUCTION MOTOR STARTING WITH LOADED GENERATOR

FIGURE 10

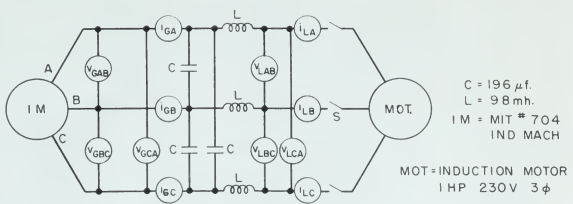




11 - a. LINE TRANSIENTS-LIGHTLY LOADED INDUCTION MOTOR



11 - b. LINE TRANSIENTS -HEAVILY LOADED INDUCTION MOTOR



TRANSIENTS FOLLOWING INDUCTION MOTOR STARTING WITH UNLOADED GENERATOR

FIGURE 11



period, naturally, first increased abruptly and then exponentially diminished to a steady-state value not much higher than that value prior to the load change. This was a relatively light load addition, though believed to be not unlike a condition that is common on an expanded scale in power distribution systems. No transients of any consequence are observed. The length of the transient period is governed principally by the characteristics of the load.

There is noted, superimposed on the envelope of the sinusoidal line current,  $i_L$ , an oscillating component of small amplitude and low frequency. This is thought to be a feature introduced by the motor and its connected load.

At the machine terminals, current and voltage vary as indicated by the traces of Figure 10-b. As can be seen, slightly different load conditions prevailed in the run during which this oscillogram was recorded. The tendency for terminal voltage to remain nearly constant is partly due to the high degree of saturation at which the machine was being operated. The stator current dip was caused by a decrease in excitation current as the imaginary part of the impedance presented to the machine terminals became less negative while the motor was gathering speed.

The next step was to produce the oscillogram of Figure 11-a, showing the effects in the line of an induction motor being started with an unloaded generating unit. The oscillogram presented in Figure 11-b is for a similar condition except that here the induction motor was heavily loaded.



period, naturally, that increased abruptly and then  
exponentially diminished to a steady-state value not  
much higher than that value prior to the load change.  
This was a relatively light load condition, though believed  
to be not unlike a condition that is common on an expanded  
scale in power distribution systems. No transient of any  
consequence was observed. The length of the transient  
period is governed principally by the characteristics of  
the load.

There is noted, superimposed on the envelope of the  
sinusoidal line current, i.e., an oscillating component of  
small amplitude and low frequency. This is thought to be  
a feature introduced by the motor and its connected load.  
As the machine terminals, current and voltage vary  
as indicated by the traces of figures 11-4, we can be seen,

slightly different load conditions prevailed in the run  
during which this oscillation was recorded. The tendency  
for terminal voltage to remain nearly constant is readily  
due to the high degree of regulation of which the machine  
was being operated. The larger output it was desired to  
a decrease in excitation current at the load side of the  
the impedance presented to the machine terminals becomes  
less negative while the motor was generated power.

The next step was to produce the condition of figure  
11-5, showing the effects in the line of an induction motor  
being started with an unbalanced generating unit. The oscillogram  
was presented in figure 11-6 in the a similar condition  
except that here the induction motor was heavily loaded.

In neither case do the line transients show instantaneous values for current or voltage that might cause a generating unit casualty. In the latter trial, the induction motor load was approximately one-fourth the maximum power output obtainable with the combination of capacitance and inductance used. As the motor-starting load is further increased, the induction machine eventually will lose excitation and fail to generate. As in the short circuit case, no dangerous currents or voltages would be produced. In comparison, the instantaneous line current resulting from starting an induction motor with a synchronous generator may be six times the peak current of the steady state<sup>10</sup>.

d.) Unloading - To complete the study of load variations on the induction generating unit, it was necessary to consider the effects of abrupt load removals. For this purpose the generating unit was loaded with parallel banks of resistors and then unloaded by cutting out resistance in three-phase sets. Figure 12-a illustrates both the line and the machine electrical transients following a sudden load reduction of 50 percent. The accompanying oscillogram of Figure 12-b was obtained by dropping the remainder of the load.

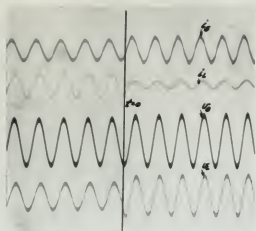
The traces of Figure 12-c were recorded when the entire load was dropped in one step. In the first and third instances the initial load was approximately 3 KW. In all cases the load was symmetrical; thus, the effects in only one phase are illustrated. Again, in all three cases, the value of

In either case the line currents show irregularities  
 values for current or voltage that might cause a commencing  
 unit casualty. In the latter case, the induction motor  
 load was approximately one-third the maximum power output  
 obtainable with the combination of speed and induction  
 used. As the motor-bearing load is further increased, the  
 induction machine eventually will lose excitation and fall  
 to generator. As in the short circuit case, no dangerous  
 currents or voltages would be produced. In comparison, the  
 instantaneous line current resulting from starting an  
 induction motor with a synchronous generator may be six  
 times the peak current of the steady state.

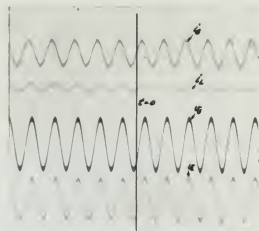
#### 4.1 Induction

To obtain the ratio of load vari-  
 ations on the induction generator load, it was necessary to  
 consider the effects of actual load changes. The ratio  
 between the resulting load and the initial load was  
 of resistance and then adjusted by voltage and resistance in  
 three-phase case. Figure 1-2 illustrates with the line  
 and the machine electrical constants following a sudden  
 load reduction of 50 percent. The synchronous generator  
 of Figure 1-2 was obtained by applying the constant of the  
 load.

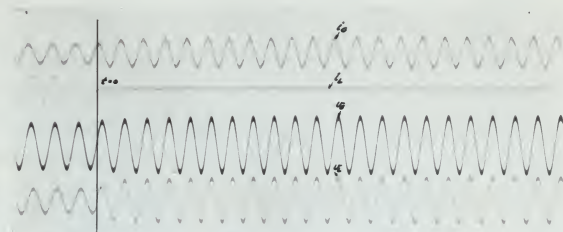
The traces of Figure 1-2 were repeated with the entire  
 load was dropped in one step. In the first two steps the  
 the initial load was approximately 30%. In all cases the  
 load was symmetrical; that, the effects in any one phase  
 are illustrated. Again, in all three cases, the ratio of



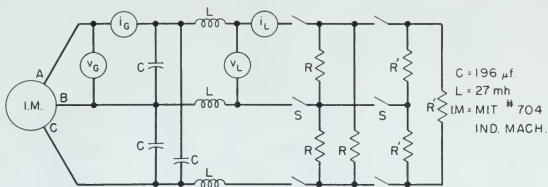
12-a. REMOVAL OF ONE HALF  
THE LOAD



12-b. REMOVAL OF REMAINING  
HALF THE LOAD



12-c. REMOVAL OF ENTIRE LOAD



TRANSIENTS FOLLOWING ABRUPT UNLOADING  
FIGURE 12



shunt capacitance was the same as for all previous transient investigations. However, the value of the series inductance was increased somewhat in order to give poor voltage regulation between the unloaded and the loaded conditions. By doing this, it could be expected that voltage surge, if it existed, would be demonstrated more clearly. An examination of the three oscillograms shows that no voltage surge occurred. The line voltage instantaneously jumps to a value nearly equal to the new steady-state value. The remaining small increase in voltage is attained gradually in the next quarter of a second. The generated voltage remains nearly constant; the small change involved is completed within 5 cycles. Upon decreasing the load by one-half, the line current ( $i_L$  of Figure 12-a) exhibits a remarkable transient effect. It appears that this transient is of an extremely over-damped nature.

Unbalanced loading after initiation of the transient produces a harmonic in the final stator current wave,  $i_g$ , of all three oscillograms. The voltage trace, however, is consistently a pure sinusoid. Here, as in a transformer, the exciting component of current has varied irregularly to preserve sinusoidal voltage output.

e.) Frequency Variation - In all of the oscillograms recording the effects of sudden changes in load, it is noted that frequency decreased with increasing load. This is due to the change in slip accompanying power variations. As power is increased from zero, the slip is approximately

shunt capacitance was the same as for all previous transformer investigations. However, the value of the series inductance was increased somewhat in order to give near voltage regulation between the unloaded and the loaded conditions. By doing this, it could be expected that voltage surge, if it existed, would be demonstrated more clearly. An examination of the three oscillograms shows that no voltage surge occurred.

The line voltage instantaneously jumps to a value nearly equal to the new steady-state value. The remaining small increase in voltage is obtained gradually in the next quarter of a second. The generated voltage remains nearly constant; the small change involved is completed within 5 cycles. Upon decreasing the load to one-half, the line current (at of figure 18-a) exhibits a remarkable transient effect. It appears that this transient is of an extremely over-damped nature.

Unbalanced loading when induction of the transformer produces a harmonic in the line current wave,  $i_g$ , of all three oscillograms. The voltage wave, however, is consistently a pure sinusoid. Here, as in a transformer, the exciting component of current has varied considerably to produce sinusoidal voltage output.

2.1 Frequency Variation - In all of the oscillograms recording the effects of sudden changes in load, it is noted that frequency decreases with increasing load. This is due to the change in slip accompanying power variations. As power is increased from zero, the slip is correspondingly

proportional to power. The inertia of the generator rotor and connected drive motor maintained essentially constant speed through each load change. The increase in slip speed causes an equal decrease in what is conventionally termed synchronous speed. With a fixed number of poles the result is a proportional decrease in frequency.

Conclusions drawn from the discussion of experimental results of transient investigation are included in Chapter IV.





#### IV. CONCLUSIONS

The work performed with the self-excited induction generator with series inductance compounding leads to the following conclusions:

1. The no-load characteristics of this generating unit are determined by the exciting capacitance and machine constants.
2. With load applied, the line voltage regulation is improved as series inductance is reduced, holding shunt capacitance constant.
3. With constant series inductance, the line voltage regulation is improved by raising the shunt capacitance.
4. Providing power service is continuous for the range of unity power-factor loads from no-load to short circuit, the generating unit will not cease generation for any lagging power factor load. The maximum power output may be increased by either reducing series inductance or increasing shunt capacitance.
5. Loss of power due to insufficient magnetizing inductance does not occur before the generating unit has delivered maximum power obtainable with a given combination of inductance and capacitance.

IV. CONCLUSIONS

The work performed with the self-excited induction generator with series inductance compensating leads to the following conclusions:

1. The no-load characteristics of this generating unit are determined by the exciting capacitance and machine constants.
2. With load applied, the line voltage regulation is improved as series inductance is reduced, holding shunt capacitance constant.
3. With constant series inductance, the line voltage regulation is improved by raising the shunt capacitance.
4. Providing power service is continuous for the range of unity power-factor loads from no-load to short circuit, the generating unit will not cease generation for any lagging power factor load. The maximum power output may be increased by either opening series inductance or increasing shunt capacitance.
5. Loss of power due to inductive reactance inductance does not occur before the generating unit has delivered maximum power maintainable with a given combination of inductance and capacitance.

6. Efficiency of the generating unit is poor for partial loads due to the presence of a large excitation current.
7. The transients following faults and sudden load changes do not produce excessive currents or potentials in the generating unit or line. Sustained short-circuit current is dependent upon the relative values of series inductance and shunt capacitance.

From an engineering standpoint, it seems that the design of a practical induction generating unit based on present knowledge will involve a compromise between voltage regulation and power output on the one hand and stability and efficiency on the other. Good voltage regulation may be obtained by working the generator highly saturated; however, excessive inefficiencies will result. Capacitive compensation can produce desired voltage characteristics under load, but may lead to excessive values of terminal voltage and machine current if the line becomes shorted. Moreover, the shunt capacitance must be a value low enough not to produce excessive open circuit voltage; yet, high enough to assure generation continuity through a reasonable range of lagging power factor loads.

Faults will not produce dangerous currents and potentials if inductive compensation is employed. Inductive compensation

- 6. Efficiency of the generating unit is poor for partial loads due to the presence of a large excitation current.
- 7. The generator's frequency falls and voltage load changes do not produce sensitive changes in the generating unit or line. Increased short-circuit current is observed upon the relative values of series inductance and capacitance.

From an engineering standpoint, it seems that the analysis of a practical induction generating unit based on present knowledge will involve a comparison between voltage regulation and power output on the one hand and efficiency and efficiency on the other. Good voltage regulation may be obtained by varying the generator's field resistance; however, excessive field resistance will result. Excessive current can produce excessive voltage drops across the motor load, but may lead to excessive voltage of terminal voltage and machine current in the line between motor and generator. The most serious case is a case in which the voltage between generator and motor is too low. This is the case in which the generator's field resistance is too high. Excessive field resistance will result in excessive current and excessive voltage drops across the motor load.

It is noted that the generator's efficiency is not necessarily high. It is noted that the generator's efficiency is not necessarily high. It is noted that the generator's efficiency is not necessarily high.

may lead to discontinuous voltage generation, but this will not occur before reaching the point of maximum power. Furthermore, and equally important, inductive values that lead to this condition of instability also result in the maximum power obtainable with a given machine size. In the limit, series inductance may be reduced to zero, i.e., no compensation, but this condition causes voltage regulation to become rapidly worse as load power factor becomes more lagging.

Inductive compensation may be adjusted to give continuous power generation for all lagging power factor loads. However, in order to carry reasonable loads, the unit must have shunt capacitors of large size, and will, therefore, suffer from the above-mentioned disadvantages. Again, voltage regulation is far from satisfactory. It is believed that a compromise design for a self-excited induction generator, statically compensated, will require inductive compensation. The value of inductance will be selected after considering stability, power output and voltage regulation for expected load demands.

may lead to discrimination against generation, but this will not occur before reaching the point of maximum power.

Furthermore, and equally important, inductive values lead to the possibility of inductively also coming in for

maximum power obtainable with a given maximum size. In the latter series inductance can be reduced to zero, i.e.,

no inductance, but this condition never occurs in practice. This is because of the fact that inductance cannot be reduced to zero in practice.

Inductive reactance can be reduced to give other times power generation, but this is only possible in the latter

However, in order to vary reactance in this way, it must have about capacity of large size and will, therefore,

be able to store the energy required. It is believed that a capacitor design for a half-cycle inductor capacity

for inductively compensated, all inductive inductive capacity. The value of inductance will be constant at this

condition. Inductively, power output and other conditions are affected in this manner.

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## V. RECOMMENDATIONS

Poor voltage regulations is one of the major disadvantages of the induction generator without compensation. Static compensation improves voltage regulation, but introduces other objectionable characteristics of operation. Adjustable compensation may be a satisfactory solution. For this purpose, capacitive compensation would not be acceptable because smoothly-varying capacitors in power sizes are not, at present, feasible. On the other hand, an adjustable inductance could be continuously increased to give the desired line voltage characteristic.

One scheme that appears promising involves use of an automatically controlled inductance as series compensation. As load increases, line voltage would be held nearly constant by decreasing the inductance through a regulatory system. The inductive reactance may be supplied by a saturable core reactor, or a movable core inductance coil. At this time, it is felt that sufficient knowledge of the induction generator has been gained to permit a study of self-adjusting voltage regulation from a servo-mechanisms viewpoint.

The advantages of an induction generator will become more apparent at higher frequencies. Size and cost of capacitances could then be considerably reduced. Also, the squirrel-cage rotor will permit relatively high rotor speeds. For these reasons it is recommended that further work be performed at 400 c.p.s.



Two voltage regulators is one of the major disadvantages of the induction generator without compensation. Static compensation improves voltage regulation, but influences other objectionable characteristics of operation. Adjustable compensation may be a satisfactory solution. For this purpose, capacitor compensation would not be acceptable because essentially-varying capacitors in power lines are not, at present, feasible. On the other hand, an adjustable inductance could be continuously increased to give the desired low voltage characteristic.

The scheme that appears promising involves use of an automatically controlled inductance as better compensation. As load increases, the voltage would be held nearly constant by diverting the inductance through a reactor system. The inductive reactance may be limited by a saturable core reactor, or a movable core inductor coil. At this time, it is felt that further work should be done in induction generator has been gained in terms of a study of self-induction voltage regulation from a mathematical viewpoint.

The advantages of the induction generator will become more apparent if higher frequencies. Also and most of capacitors could then be considerably reduced. Also, the electrical-iron losses will be reduced relatively high losses. For these reasons it is recommended that further work be continued at this time.

Frequency regulation should also be investigated with a view toward reducing the frequency transient following changes in load demand. For practical use in a turbo-generator set, the speed of the induction generator must be varied with load demand to maintain constant frequency. The conventional fly-ball governor of the turbine must be modified to provide for control of spring tension. This control will be actuated by deviations from the desired frequency. For parallel operation, load will be distributed, as now, by adjusting the throttle opening. The combined rotating inertia of the turbine and generator will make transient frequency variations unavoidable. A study of the engineering problems involved in frequency control should be conducted by both analytical and experimental means.

In conclusion, it is suggested that present disadvantages of the induction generator may be reduced somewhat by re-designing the electric and magnetic circuits of the induction machine. Machine currents could be reduced by specially formed rotor conductors. Operation in relatively saturated regions may be tolerated if the volume of the iron in the magnetic circuit could be appreciably reduced.

The Commission will also be investigating with  
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In conclusion, it is suggested that the transfer of the  
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VI. APPENDIX

The method that has been developed for determining...  
relationships was applied to produce the effect of in-  
sulative temperature and flow velocity on pressure ratios  
for some experiments and some observations for illustrative  
purposes. A qualitative description of this procedure will  
follow.

Figure 1 shows the experimental arrangement as provided  
by detailed description in the field notes and presented by  
a general description herein by the condition of some  
experiments. A detailed description of the apparatus  
experimentally was given by Figure 1-1. In the lower  
region of this chart, points were obtained by connecting  
the pressure measuring points to a differential,  
D-type pressure gauge that provided an air pressure indicator  
from 100 to 1000 psia with an accuracy of 1 percent of nominal  
without error. Most of the flow-velocity data was  
obtained by operating the differential machine under the load  
as a differential-pressure measuring and recording device of  
steady pressure. Terminal velocity and current were  
measured and plotted to show the typical relationship curves  
of Figure 1-1. Operating on the equation, velocity of  
flow is, it is seen that the load conditions are  
constant over the range of the constant velocity 1-1-1

VI. APPENDIX

... (The text in this block is mostly illegible due to extreme blurriness and low contrast. It appears to be a continuation of the technical description from the previous block, discussing experimental results and relationships between variables like pressure, velocity, and load conditions.)

The Commission, in its report, has stated that the
 present system of taxation is not only unfair but
 also inefficient. It is a system which has
 become obsolete and is no longer adapted to
 the needs of the country. The Commission
 has recommended that the present system
 should be replaced by a system which is
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 has also recommended that the present
 system should be replaced by a system
 which is fair, efficient and simple.

#### CONCLUSION

The Commission has recommended that the
 present system of taxation should be replaced
 by a system which is fair, efficient and
 simple. The Commission has also
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 should be replaced by a system which
 is fair, efficient and simple. The
 Commission has also recommended
 that the present system should be
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 efficient and simple.

## A. DETAILED PROCEDURE

The method that Friauf<sup>1</sup> developed for performance calculations was modified to include the effect of inductive compounding and then employed to predict values for shunt capacitance and series inductance for laboratory work. A qualitative description of this analytical work follows.

Voltage build-up in an induction machine is initiated by residual magnetism in the field poles and progresses to a potential determined uniquely by the magnitude of shunt capacitance. A no-load saturation curve was obtained experimentally and appears in Figure A-3. In the lower region of this curve, points were obtained by connecting the induction machine through a variac to a 230-volt, 3-phase power supply that resulted in no power transfer from line to stator for each of a number of terminal voltage values. Data in the high-voltage region was obtained by operating the induction machine under no load as a capacitor-excited generator for various values of shunt capacitance. Terminal voltage and current were recorded and plotted to give the typical saturation curve of Figure A-3. Referring to the equivalent circuit of Figure A-2, it is seen that at no load conditions the current from the terminals of the machine (marked  $t-t'$ )

### A. INITIAL DESIGN

The initial design developed for performance calculations was modified to include the effect of inductive reactance and then applied to power values for many locations and series numbers for industry work. A qualitative description of this modified work follows.

Voltage build-up in an induction machine is indicated by terminal magnetism in the field wind and progresses to a potential saturation voltage by the magnitude of stator

excitation. A no-load saturation curve was obtained experimentally and appears in Figure 4-2. In the lower portion of this curve, points were obtained by connecting the induction machine through a series of 100-ohm

3-phase power supply that resulted in no power transfer from line to stator for each of a number of terminal voltage values. Data in the high-voltage region was

obtained by operating the induction machine under no load as a synchronous motor generator and various values of short-circuits. Terminal voltage and current were

recorded and plotted to give the typical saturation curve of Figure 4-2. The portion of the saturation curve of Figure 4-2 is in fact that of no load induction for

current from the terminals of the machine (Figure 4-2).

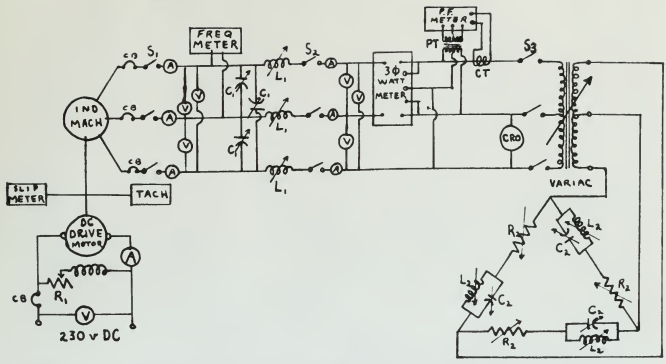


FIGURE A-1-CIRCUIT DIAGRAM FOR STEADY STATE OPERATION

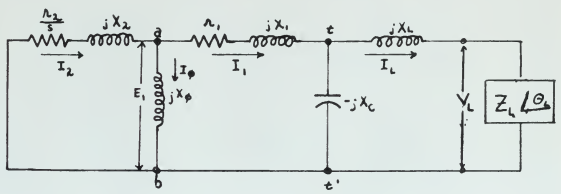
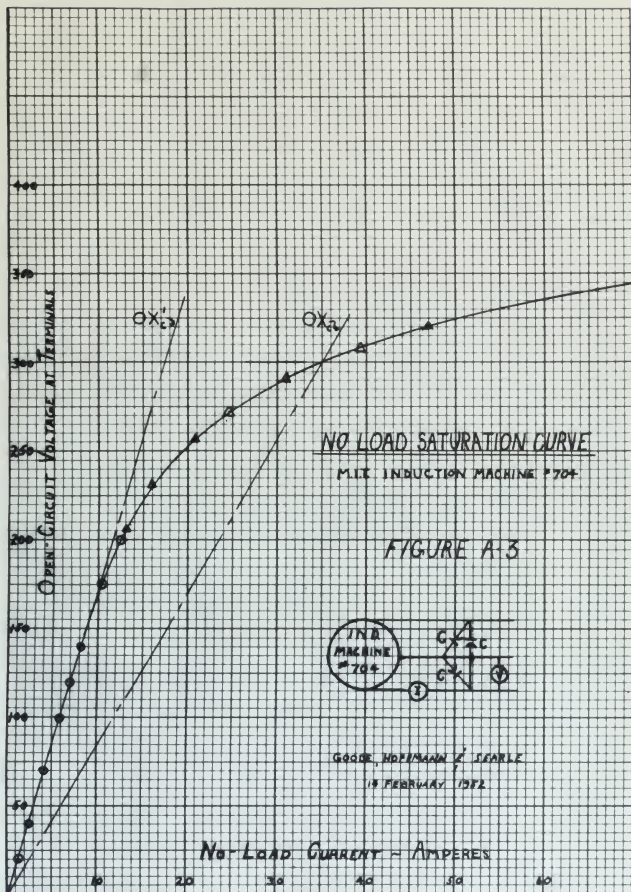


FIGURE A-2-EQUIVALENT CIRCUIT OF ONE PHASE









is essentially equal in magnitude to the magnetizing branch current,  $I_g$ . It will be noted that the slope of the straight line of Figure A-3, indicated by  $OX'_c$ , represents a critical value of capacitive reactance, below which the generator will fail to build up voltage. Open-circuit voltage is fixed by the intersection of the saturation curve with the straight line,  $OX_c$ , the slope of which is fixed by the value of shunt capacitance.

Knowing the machine constants, the stator impedance drop was calculated for various values of no-load excitation current. By subtracting vectorally these impedance drops from the corresponding terminal voltages on a per phase basis, values of air-gap voltage,  $E_1$ , were determined.

It was assumed that there was no resistance included in the magnetizing branch. The susceptance of the magnetizing branch can then be expressed by the relation:

$$Y_\phi = \frac{I_\phi}{E_1} \quad (1)$$

Magnetizing susceptance,  $Y_\phi$ , was calculated and plotted as a function of air-gap voltage,  $E_1$ . The result is the susceptance curve of Figure A-4. The distance o-a along the abscissa of Figure A-4 represents a minimum value of magnetizing susceptance below which no air-gap voltage will be generated. The existence of this minimum magnetizing susceptance is a direct consequence of the critical value of excitation reactance.

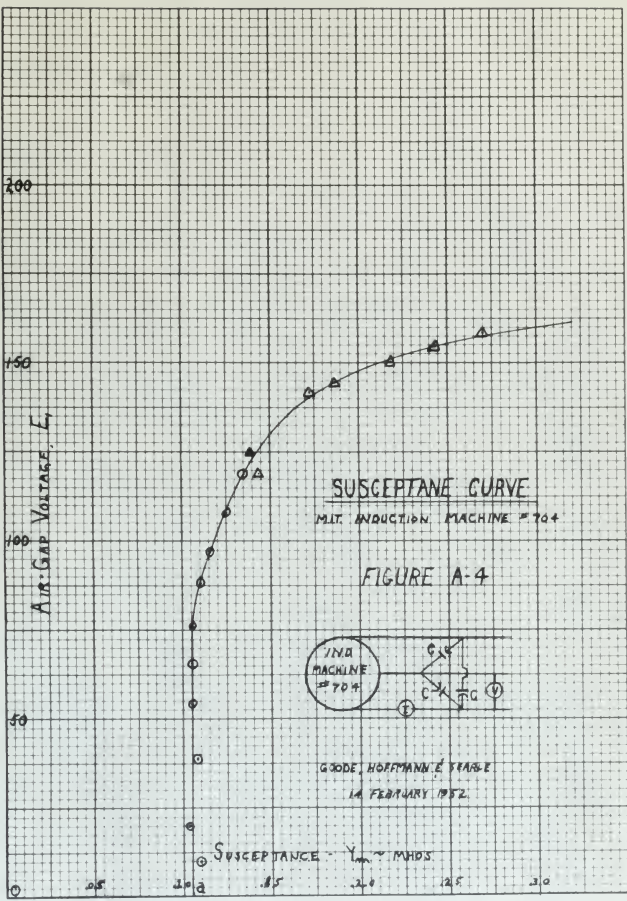
is essentially equal in magnitude to the magnetizing branch current,  $I_m$ . It will be noted that the slope of the straight line of figure 3-2, indicated by  $\tan \alpha$ , represents a critical value of capacitive reactance, below which the generator will fail to build up voltage. Open-circuit voltage is fixed by the intersection of the saturation curve with the straight line,  $\tan \alpha$ , the slope of which is fixed by the value of armature reactance.

Knowing the machine constants, the steady impedance drop was calculated for various values of no-load excitation current. By superimposing vectorially these impedance drops from the corresponding terminal voltages on a per phase basis, values of air-gap voltage,  $E_a$ , were determined.

It was assumed that there was no resistance included in the magnetizing branch. The reactance of the magnetizing branch can then be expressed by the relation:

$$X_m = \frac{E_a}{I_m} \quad (1)$$

Magnetizing reactance,  $X_m$ , was calculated and plotted as a function of air-gap voltage,  $E_a$ . The result is the saturation curve of figure 3-2. The maximum value of open-circuit voltage is represented by a constant value of magnetizing reactance, below which no air-gap voltage will be generated. The existence of this minimum magnetizing reactance is a direct consequence of the limited value of field winding resistance.





Referring now to the equivalent circuit of Figure A-2, Kirchoff's current equation applied to the point a, will result in the expression:

$$I_2 = I_\phi + I_1 \quad (2)$$

which may be expressed as:

$$E_1 Y_2 = E_1 Y_\phi + E_1 Y_1.$$

$Y_2$  is that admittance entirely to the left of points a - b;  
 $Y_1$  is that admittance entirely to the right of points a - b;  
 and  $Y$  is the admittance of the magnetizing branch.

Rearranging terms and employing the assumption of purely reactive impedance in the magnetizing branch, the final desired expression for magnetizing susceptance is,

$$Y_\phi = \text{Im} [Y_1] - \text{Im} [Y_2] \quad (3)$$

The admittances  $Y_2$  and  $Y_1$  may be expressed as:

$$Y_2 = \frac{1}{r_2/s + j x_2} \quad (4)$$

and  $(5)$

$$Y_1 = \left[ r_1 + j x_1 + \frac{1}{\frac{1}{j x_m} + \frac{1}{j x_m + |Z|(\cos \phi + j \sin \phi)}} \right]^{-1}$$

An admittance diagram after the manner of Friauf<sup>1</sup> was then prepared showing the locii of  $Y_1$  and  $Y_2$  on a complex plane. First, it was necessary to determine experimentally the stator and rotor constants of the machine as described elsewhere. From equation (4) it is seen that for a given



Referring now to the equivalent circuit of Figure 4-2, Kirchhoff's current equation applied to the point  $a$ , will result in the equation:

$$(2) \quad I_2 = I_1 + I_3$$

which may be expressed as:

$$E_1 Y_2 = E_1 Y_1 + E_2 Y_1$$

$Y_2$  is the admittance entirely to the left of point  $a - b$ ;  $Y_1$  is the admittance entirely to the right of point  $a - b$ ; and  $Y$  is the admittance of the magnetizing branch.

Rearranging terms and applying the assumption of purely reactive impedance in the magnetizing branch, the final desired expression for magnetizing susceptance is:

$$(3) \quad [E_2 Y_1] - [E_1 Y_1] = I_3$$

The admittance  $Y_1$  and  $Y_2$  may be expressed as:

$$(4) \quad Y_1 = \frac{1}{Z_1} = \frac{1}{Z_2 + j X_m}$$

(5) and

$$Y_2 = \frac{1}{Z_2} = \frac{1}{Z_2 + j X_m}$$

An admittance diagram after the manner of Figure 4-3 was then prepared showing the locus of  $Y_1$  and  $Y_2$  on a complex plane. First, it was necessary to determine experimentally the error and verify constants of the machine as described elsewhere. From equation (5) it is seen that for a given

machine,  $Y_2$  is a unique function of slip. With slip as a parameter, the locus of  $Y_2$  was plotted as indicated in Figure A-5(a).

It can be shown that the locus of admittance  $Y_1$ , with magnitude of load impedance,  $Z_L$ , as a parameter, is a circle for a given machine when shunt capacitance, series inductance, and load power factor angle are all held constant. The radius can be expressed by:

$$\text{radius} = \frac{\frac{1}{2} X_c \frac{X_c}{X_c - X_s} \sec \phi}{\left( X_1 + \frac{1}{2} X_c \frac{X_c}{X_c - X_s} \tan \phi \right)^2 + \left[ X_1 - \frac{1}{2} X_c \left( \frac{X_c - 2X_s}{X_c - X_s} \right) \right]^2 - \left( \frac{1}{2} X_c \frac{X_c \sec \phi}{X_c - X_s} \right)^2} \quad (6)$$

The center of the circle is located as the point having an abscissa of:

$$\frac{X_1 + \frac{1}{2} X_c \frac{X_c}{X_c - X_s} \tan \phi}{\text{(same denominator as Eq. 6)}} \quad (7)$$

and an ordinate of:

$$\frac{-X_1 + \frac{1}{2} X_c \frac{X_c - 2X_s}{X_c - X_s}}{\text{(same denominator as Eq. 6)}} \quad (8)$$

Such a circle locus for  $Y_1$  is drawn in Figure A-5(a) labeled unity power factor. As the load impedance angle is varied to give lagging power factors, a family of circles is found for the resulting loci of  $Y_1$ . The centers of these circles move to the left as the load power factor decreases. All circles pass through the open-circuit point and the short-circuit point, because for load impedance

... is a unique solution of the ...  
 ... the locus of ...  
 ...

If we ... the locus of ...  
 ... as a parameter, in a  
 circle for a given ...  
 ... and that power factor ...  
 ... can be expressed as:

$$(16) \quad \frac{\frac{1}{2} X \frac{1}{2}}{e^{i\omega t} - \omega X} = \frac{1}{2} X \frac{1}{2} + \dots$$

The radius of the circle is located at the point ...  
 ...

$$(17) \quad \frac{\frac{1}{2} X \frac{1}{2} + \dots}{\dots}$$

... can be obtained as:

$$(18) \quad \frac{\frac{1}{2} X \frac{1}{2} + \dots}{\dots}$$

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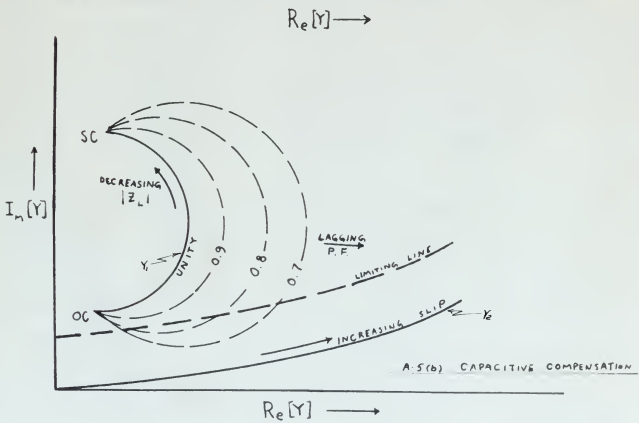
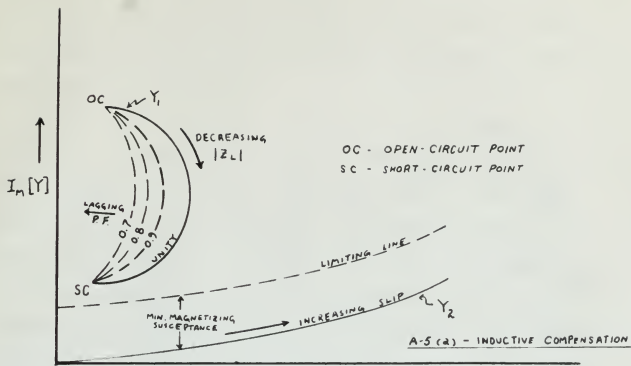


FIGURE A-5 ADMITTANCE LOCI



equal to infinity or zero, power factor is meaningless. As brought out earlier, the open-circuit point is fixed by the value of shunt capacitance. The short-circuit point falls below the open-circuit point and moves nearly vertically up or down with increasing or decreasing series inductance respectively.

From equation (3) it is seen that magnetizing susceptance,  $Y_\phi$ , is equal to the vertical distance from the locus of  $Y_2$  to the locus of  $Y_1$ . A straightforward mathematical analysis of the performance of the induction generator may be commenced at this point. In brief, the method involves graphically picking off values of magnetizing susceptance for selected values of admittance,  $Y_1$ . Then, use is made of the susceptance curve to determine air-gap voltage. Having a value for air-gap voltage and a corresponding value of admittance,  $Y_1$ , application of simple circuit analysis will lead to calculated values of load voltage,  $V_L$ , and load current,  $I_L$ , of the equivalent circuit, Figure A-2.

This method of performance calculation is found in the notes of Dr. Friauf<sup>1</sup> and experimental confirmation is included in the work by Swift<sup>2</sup>. For this thesis the method served to establish orders of magnitude for values of shunt capacitance and series inductance necessary for prospective laboratory investigations. It should be noted that as the inductance is reduced, the magnetizing susceptance,

equal to infinity or zero, power factor is meaningless. As through out earlier, the open-circuit point is fixed by the value of shunt capacitance. The short-circuit point falls below the open-circuit point and moves nearly vertically up or down with increasing or decreasing series inductance respectively.

From equation (1) it is seen that sagging impedance factor,  $V_p$ , is equal to the vertical distance from the focus of  $V_p$  to the focus of  $V_s$ . A straightforward mathematical analysis of the performance of the induction generator may be commenced at this point. In brief, the method involves graphically finding off values of sagging impedance for selected values of admittance,  $Y_1$ . Then, use is made of the susceptance curve to determine air-gap voltage. Having a value for air-gap voltage and a corresponding value of admittance,  $Y_1$ , application of simple circuit analysis will lead to calculated values of load voltage,  $V_L$ , and load current,  $I_L$ , of the equivalent circuit.

Figure 4-2.

This method of performance calculation is found in the notes of Dr. Collins' and experimental confirmation is included in the work of Smith<sup>12</sup>. For this reason the method seems an excellent means of obtaining the values of short-circuit current and series inductance necessary for prospective impedance investigations. It should be noted that as the impedance is reduced, the sensitivity of the

$Y_{\phi}$ , may become less than the minimum value for sustaining voltage generation. When this condition prevails the locus of  $Y_1$  has intersected the curve marked limiting line of Figure A-5. The limiting line is constructed by following the curvature of the locus of  $Y_2$  at a vertical distance above equal to the value of minimum magnetizing susceptance.

It might be pertinent to point out here that if admittance loci are similarly plotted for the case of an induction generator with capacitive, rather than inductive, compensation, two important changes occur. Loci are indicated qualitatively in Figure A-5(b) for this case. Obviously, the locus of  $Y_2$  remains unchanged. However, the short-circuit point is now found nearly vertically above the open circuit point. Moreover, in opposition to the previous case with inductive compensation, each family curve representing the locus of  $Y_1$  for lagging power factors moves to the right as the load impedance angle increases. As illustrated in the sketch of Figure 5-A(b), this means that voltage generation would collapse for certain lagging power factor loads.

In preparation for the laboratory work, the equivalent circuit parameters, Figure A-2, were experimentally determined in accordance with A.I.E.E. standards. The values of machine constants so obtained are listed in Table A-1.



1907 was found to be the same as the results  
of the previous year. The results of the  
year 1907 are given in the table below.  
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in the table below. The results of the  
year 1907 are given in the table below.

It is seen from the table that the  
results of the year 1907 are the same  
as the results of the previous year.  
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in the table below. The results of the  
year 1907 are given in the table below.

TABLE A-IMachine Constants for M.I.T. Induction Machine No. 704

$r_1$	=	0.43 ohms
$r_2$	=	0.174 ohms
$x_1$	=	0.58 ohms
$x_2$	=	0.58 ohms
$x_\phi$	=	7.79 ohms

A value of shunt capacitance was selected that would give an open-circuit voltage not exceeding a safe upper limit. A value of series inductance was then determined which would locate the short-circuit point near, but above, the limiting line. With these values of capacitance and inductance, the test equipment as shown in the circuit diagram, Figure A-1, was set up. The induction machine was operated as an eight-pole machine and was driven with a d-c motor. Speed was controlled by manually varying field resistance,  $R_1$ , to maintain 60 c.p.s. output of the generator as indicated by the frequency meter.

It was found necessary to make slight readjustments of the values of inductance,  $L_1$ , and capacitance,  $C_1$ , as previously determined to assure continuous voltage generation and to provide balanced conditions for the three phases. Upon completion of each run, the reactance of these elements was measured.

For the steady-state investigation with constant parameters, the generator was operated at power factors varying

Table 1-1

Reaction Coefficients for A.C. I. Induction Machine at 75%

$x_1$	=	0.43 ohms
$x_2$	=	0.17 ohms
$x_3$	=	0.32 ohms
$x_4$	=	0.35 ohms
$x_5$	=	7.75 ohms

A value of short-circuiting was selected that would give an open-circuit voltage not exceeding a safe voltage limit. A value of excitation inductance was then determined which would locate the short-circuit point near, but above the limiting line. With these values of reactance and inductance, the test equipment is shown in the circuit diagram, figure 1-1, was set up. The induction machine was connected in an eight-coil machine and was driven with a d-c motor. Speed was controlled by manually varying field resistance,  $R_f$ , to maintain 60 a.c. volts on the generator as indicated by the frequency meter.

It was found necessary to make slight readjustments of the value of inductance,  $L$ , and reactance,  $X$ , as previously mentioned to secure maximum voltage across the arm and to provide balanced conditions for the three phases. Upon completion of each run, the resistance of each element was measured.

For the steady-state investigation also constant voltage motor, the generator was started at about twenty percent

from .15 lagging to .75 leading by adjusting the load components  $R_2$ ,  $C_2$ , and  $L_2$ . The data recorded is shown in the Appendix (Runs I - VII) and is plotted in Figures 1, 2, and 3.

Further investigation was concerned with the possibility of improving voltage regulation by decreasing the value of series inductance,  $L_1$ . First (Run VIII), the same value of shunt capacitance,  $C_1$ , was used as in the previous test. Then (Run IX), to demonstrate the effect of saturation, the value of  $C_1$  was decreased, while  $L_1$  remained at the lower setting. These runs were made at unity power factor and, for comparison, are plotted with the unity power factor result of Run I. The data appears in the Appendix, and is plotted in Figures 5, 6, and 7.

For all the above laboratory work, three-phase balance was maintained at generator and load within 5 percent. The generated waveform was observed on an oscilloscope.

The transient behavior of the induction generator with inductive compensation was investigated. A 3-blade "guillotine" switch was inserted in the circuit of Figure A-1 at  $S_3$  with its secondary connected to provide single- and three-phase short circuits. Voltage and current transients were recorded using a Westinghouse portable oscillograph, with six recording elements. The traces were roughly adjusted to indicate the balanced conditions existing in the circuit. A time trace was not included

... is applied to the ... by ... the ...  
... The ... is ...  
... in the ... (I - VII) ... in ...

I, V, and 3.

Further investigation was concerned with the possibility  
of improved voltage regulation by decreasing the value of  
series inductance,  $L_s$ . First (Run VIII), the same value of  
series inductance,  $L_s$ , was used as in the previous test.  
Then (Run IX), to demonstrate the effect of increasing  
the value of  $L_s$  was decreased, while  $L_p$  remained at the  
same value. Then runs were made at still lower series  
inductance, and plotted with the other series factor  
results of Run I. The best results in the Appendix, and its  
plotted in Figure 1, 2, and 3.

For all the above secondary tests, the same primary  
was maintained at constant and load with a constant. The  
secondary inductance was measured as in Appendix.

The primary inductance of the transformer was  
also measured. The inductive compensation was investigated. A  
"gallium" section was inserted in the circuit to provide  
A-1 at 25 kHz. The secondary connected to provide single  
and three-phase short circuits. Voltage and current  
transients were recorded using a synchronous oscilloscope  
connected with the secondary circuit. The traces  
were normally obtained in addition the primary inductance  
obtained in the circuit. The traces are not included.

since the steady state appearing before the interruption is a 60 cycle trace which can be used for timing. To accomplish sudden application of load, a 1 HP, three-phase induction motor was started under load by connecting it through the "guillotine" switch. For unloading characteristics, the value of  $R_2$  was increased as a step function by using a relay-controlled "guillotine" which removed parallel resistors from the circuit.

Data compiled for the transient study are included in the Appendix and oscillograms are shown in Figures 8 - 12.

since the steady state operation during the investigation  
 is a 60 cycle wave which can be used for timing. To  
 accomplish sudden application of load, a 100, three-phase  
 induction motor was started under load by connecting it  
 through the "generator" motor. The induction coefficient  
 factor, the value of  $\mu$  was increased to a step function  
 by using a relay-controlled "generator" which removed  
 parallel resistance from the circuit.

Data compiled for the transient study are included  
 in the appendix and oscillograms are shown in figures

B. DATANAME PLATE DATA OF MACHINE USED AS A GENERATOR

M. I. T. Induction Machine No. 704 (Squirrel Cage)  
Westinghouse Type CS Induction Motor

Frame 485C	Serial No. 4884645	Style 89C120		
7.5 HP	220 volts	60 CPS	3 phase	
Poles	4	6	8	12
Amps per Terminal	19.7	19.3	25.3	33.8
Full load RPM	1710	1130	860	570
Temperature rise	50° in one hour at 100 percent load.			





## D.C. Motor

## Generator

D.C. Motor		Generator		LOAD		Efficiency		$I_3/I_L$	
V	I	V <sub>g</sub>	I <sub>g</sub>	S	V <sub>L</sub>	I <sub>L</sub>	P	$\eta_{oc}$	$\eta_{ac}$
volts	amps	volts	amps	%	volts	amps	watts	%	%
Run I PF=0.84 X <sub>L</sub> =10.25 X <sub>C</sub> =13.50	221 12.2 17.5 23.0 27.4 27.3 21.6 15.0 5.2	308 37.3 39.5 35.2 30.5 27.1 28.7 24.0 21.7 17.5 16.3	0.5 0.9 1.7 1.6 1.5 1.5 1.2 1.2 0.9	305 303 297 294 289 279 266 260 246 219 199	0.3 0.6 0.9 0.9 0.9 1.0 1.2 1.3 1.3 0.9 0.9	305 289 272 257 240 207 174 140 105 47 27	0 480 980 1280 1600 1920 2020 1800 630 520	— 17.1 7.8 3.8 3.2 2.0 1.6 1.2	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4
Run II PF=0.84 X <sub>L</sub> =10.25 X <sub>C</sub> =13.50	224 14.4 16.6 17.9 19.3 20.2 19.0 16.6 10.3 3.0	305 303 297 294 289 279 266 260 246 219 199	0.3 0.6 0.9 0.9 0.9 1.0 1.2 1.3 1.3 0.9 0.9	305 289 272 257 240 207 174 140 105 47 27	0 480 980 1280 1600 1920 2020 1800 630 520	— 17.1 7.8 3.8 3.2 2.0 1.6 1.2	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4
Run III PF=0.84 X <sub>L</sub> =10.25 X <sub>C</sub> =13.50	226 13.6 14.3 15.2 15.6 12.6 9.8 13.6	305 303 297 294 289 279 266 260 246 219 199	0.5 0.6 0.7 0.8 0.8 0.9 0.9 0.9 0.9	305 289 272 257 240 207 174 140 105 47 27	0 480 980 1280 1600 1920 2020 1800 630 520	— 17.1 7.8 3.8 3.2 2.0 1.6 1.2	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4
Run IV PF=0.83 X <sub>L</sub> =10.25 X <sub>C</sub> =13.50	226 13.0 13.6 12.2 10.4	305 299 283 276 258 237	0.5 0.6 0.6 0.6 0.6	305 289 272 257 240 207 174 140 105 47 27	0 480 980 1280 1600 1920 2020 1800 630 520	— 17.1 7.8 3.8 3.2 2.0 1.6 1.2	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4	— 27.8 14.5 11.0 7.6 5.0 3.7 2.8 2.2 1.5 1.4

(short circuit I=9.0)

Steady-State Characteristics  
All runs at 60 c.p.s.

DATA



## D.C. Motor

Run	V	I	P	$V_g$	$I_g$	$s$	$V_L$	$I_L$	R	Efficiency	$I_p/I_L$
	v	amps	watts	v	amps	%	v	amps	watts	%	
Run V	224	11.5	2600	305	36.6	0.7	305	0	0	—	—
$R_F = 0.51 \Omega$		12.1	2730	304	36.0	0.6	302	—	194	7.4	7.4
$R_L = 10.25 \Omega$		12.1	2800	303	30.3	0.6	218	4.1	500	5.0	5.0
$R_c = 13.20 \Omega$		11.7	2730	282	25.6	0.7	183	3.6	660	3.7	3.7
		11.1	2510	272	23.2	0.7	152	6.9	610	2.9	2.9
		10.4	2360	256	21.1	0.7	93	9.2	530	2.3	2.3
		9.6	2080	222	17.7	0.9	54	10.6	350	1.7	1.7
	224	4.8	1085	128	10.1	1.0	0	(short circuit I=0.8)		1.1	1.1

Run	V	I	P	$V_g$	$I_g$	$s$	$V_L$	$I_L$	R	Efficiency	$I_p/I_L$
	v	amps	watts	v	amps	%	v	amps	watts	%	
Run VII	224	11.7	2620	305	36.5	0.6	305	0	0	—	—
$R_F = 0.51 \Omega$	224	12.4	2780	305	35.8	0.4	289	—	194	14.4	14.4
$R_L = 10.25 \Omega$	226	11.6	2620	286	33.2	0.5	261	2.3	192	7.4	7.4
$R_c = 13.20 \Omega$	225	10.8	2430	276	30.2	0.6	217	4.1	240	5.2	5.2
	226	10.4	2350	271	28.2	0.6	185	5.5	256	3.4	3.4
	225	9.8	2200	261	25.2	0.7	142	7.4	258	2.4	2.4
	226	9.0	2040	251	21.6	0.6	99	8.9	218	1.5	1.5
	225	7.4	1660	231	15.9	0.6	40	10.3	88	1.5	1.5
	227	3.8	860	155	10.0	1.1	0	(short circuit I=0.8)		1.1	1.1

Run	V	I	P	$V_g$	$I_g$	$s$	$V_L$	$I_L$	R	Efficiency	$I_p/I_L$
	v	amps	watts	v	amps	%	v	amps	watts	%	
Run VIII	224	12.05	2700	305	36.3	0.4	304	0	0	—	—
$R_F = 0.51 \Omega$	224	12.4	2840	301	38.2	1.0	337	5.0	2160	7.6	7.6
$R_L = 10.25 \Omega$	224	11.6	2680	293	35.1	1.5	345	8.8	3000	4.3	4.3
$R_c = 13.20 \Omega$	223	10.4	2510	288	31.3	2.4	283	13.7	3100	2.8	2.8
	223	9.4	2340	226	25.0	2.4	287	14.0	4080	1.8	1.8
	225	8.9	2180	209	22.1	2.8	220	13.4	3360	1.6	1.6
	225	8.0	1125	85	4.0	3.2	61	5.8	480	0.7	0.7

DATA Characteristics  
Steady - State  
All runs at 60 cps.



## D.C. Motor

	V	I	P
	vols	amps	watts
Run IX	226	11.5	2600
RF=0.514g		12.1	2730
RF=10.25		12.4	2800
RF=13.20		12.1	2730
		11.7	2640
		11.1	2510
		10.4	2360
		9.6	2030
		4.8	1085

	V	I	P
	vols	amps	watts
Run X	224	11.7	2620
RF=0.514g	224	12.4	2780
RF=10.25	226	11.6	2620
RF=13.20	225	10.8	2430
	226	10.4	2350
	225	9.8	2200
	226	9.0	2040
	225	7.4	1660
	227	3.8	860

	V	I	P
	vols	amps	watts
Run XI	224	12.05	2700
RF=0.514g	224	13.4	3060
RF=10.25	224	12.4	2780
RF=13.20	223	11.7	2640
	225	10.8	2430
	226	10.4	2360
	225	9.6	2160
	227	4.8	1085

## Generator

	V <sub>L</sub>	I <sub>L</sub>	s
	vols	amps	%
	305	36.6	0.7
	304	36.0	0.6
	303	30.3	0.6
	288	27.8	0.7
	262	25.6	0.8
	272	23.2	0.7
	256	21.1	0.7
	222	17.7	0.9
	128	10.1	1.0

	V <sub>L</sub>	I <sub>L</sub>	s
	vols	amps	%
	305	34.5	0.6
	305	35.8	0.4
	286	33.4	0.5
	276	30.2	0.6
	271	28.2	0.6
	247	25.2	0.7
	257	24.6	0.6
	231	15.9	0.6
	155	10.0	1.1

	V <sub>L</sub>	I <sub>L</sub>	s
	vols	amps	%
	305	36.3	0.4
	301	38.2	1.0
	293	38.1	1.5
	228	31.3	2.4
	226	25.0	2.4
	208	22.1	2.8
	85	4.0	3.2
		11.25	

## Load

	V <sub>L</sub>	I <sub>L</sub>	R
	vols	amps	watts
	302	—	—
	218	41	900
	183	56	1030
	152	69	1050
	123	81	1010
	93	92	860
	54	104	560
	0	(short circuit I=8.9)	

	V <sub>L</sub>	I <sub>L</sub>	R
	vols	amps	watts
	305	—	—
	289	23	660
	217	41	900
	185	55	1030
	142	74	1060
	98	89	880
	40	103	410
	0	(short circuit I=8.9)	

	V <sub>L</sub>	I <sub>L</sub>	R
	vols	amps	watts
	304	50	1520
	337	88	3000
	345	137	4730
	283	140	4000
	240	134	3210
	61	5.8	350

## Efficiency

	General	Efficiency	$\frac{I_p}{I_L}$
	%	%	
	2.50	74.5	33.6
	7.4	—	—
	5.0	—	—
	3.7	—	—
	2.9	—	—
	2.3	—	—
	1.7	—	—
	1.1	—	—

	General	Efficiency	$\frac{I_p}{I_L}$
	%	%	
	11.7	70.5	16.6
	14.4	—	—
	7.4	—	—
	5.2	—	—
	3.4	—	—
	2.4	—	—
	1.8	—	—
	1.5	—	—
	1.1	—	—

	General	Efficiency	$\frac{I_p}{I_L}$
	%	%	
	53.5	78.9	68.0
	7.6	—	—
	4.3	—	—
	2.3	—	—
	1.8	—	—
	1.6	—	—
	0.7	—	—

DATA Characteristics  
Steady - State  
All runs at 60 cps









DATATransients

## 1. Three Phase Short Circuit

$$c = 196 \text{ mf} - L = 9.8 \text{ mh}$$

Before Transient:  $V_g = 255 \text{ volts}$   
 $I_g = 29 \text{ amps}$   
 $V_L = 212 \text{ volts}$   
 $I_L = 13 \text{ amps}$   
 $P_L = 4.8 \text{ KW}$   
 $f = 60 \text{ c.p.s.}$

## 2. Single Phase Short Circuit

$$c = 196 \text{ mf} - L = 9.8 \text{ mh}$$

Before Transient:  $V_g = 255 \text{ volts}$   
 $I_g = 29 \text{ amps}$   
 $V_L = 212 \text{ volts}$   
 $I_L = 13 \text{ amps}$   
 $P_L = 4.8 \text{ KW}$   
 $f = 60 \text{ c.p.s.}$

## 3. Starting Induction Motor - With Loaded Generator

$$c = 196 \text{ mf} - L = 9.8 \text{ mh}$$

Before Transient:  $V_g = 260 \text{ volts}$   
 $I_g = 28 \text{ amps}$   
 $V_L = 218 \text{ volts}$   
 $I_L = 11 \text{ amps}$   
 $P_L = 4.4 \text{ KW}$   
 $f = 60 \text{ c.p.s.}$

Results

1. Three Phase Short Circuit  
 $c = 100 \text{ m} - l = 9.8 \text{ m}$

Before Transition:  
 $V_g = 200 \text{ volts}$   
 $I_g = 38 \text{ amps}$   
 $V_L = 213 \text{ volts}$   
 $I_L = 13 \text{ amps}$   
 $V_{L'} = 4.8 \text{ kv}$   
 $I = 60 \text{ a.p.s.}$

2. Single Phase Short Circuit  
 $c = 100 \text{ m} - l = 9.8 \text{ m}$

Before Transition:  
 $V_g = 200 \text{ volts}$   
 $I_g = 38 \text{ amps}$   
 $V_L = 213 \text{ volts}$   
 $I_L = 13 \text{ amps}$   
 $V_{L'} = 4.8 \text{ kv}$   
 $I = 60 \text{ a.p.s.}$

3. Starting Induction Motor - 4400 W Motor  
 $c = 100 \text{ m} - l = 9.8 \text{ m}$

Before Transition:  
 $V_g = 200 \text{ volts}$   
 $I_g = 38 \text{ amps}$   
 $V_L = 213 \text{ volts}$   
 $I_L = 13 \text{ amps}$   
 $V_{L'} = 4.8 \text{ kv}$   
 $I = 60 \text{ a.p.s.}$

After Transient:  $P_L = 4.1 \text{ KW}$

Induction Motor Data:

1 h.p.    220 v.    3 phase  
3 amp.    60 c.p.s    4 pole

4. Starting Induction Motor - With Unloaded Generator  
 $c = 196 \text{ mf}$  -  $L = 9.8 \text{ mh}$

Before Transient:  $V_g = 300 \text{ volts}$   
 $I_g = 34 \text{ amps}$   
 $V_L = 300 \text{ volts}$   
 $I_L = 0$   
 $f = 60 \text{ c.p.s.}$

After Transient:  $P_L = 600 \text{ watts}$

Induction Motor Data as directly above.

5. Unloading  
 $c = 196 \text{ mf}$  -  $L = 27 \text{ mh}$

Full Load:  $V_g = 265 \text{ volts}$   
 $I_g = 27 \text{ amps}$   
 $V_L = 188 \text{ volts}$   
 $I_L = 8.4 \text{ amps}$   
 $P_L = 2700 \text{ watts}$   
 $f = 60 \text{ c.p.s.}$

Half Load:  $V_g = 294 \text{ volts}$   
 $I_g = 34 \text{ amps}$   
 $V_L = 280 \text{ volts}$   
 $I_L = 3.0 \text{ amps}$   
 $P_L = 1440 \text{ watts}$   
 $f = 60 \text{ c.p.s.}$



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[The following text is extremely faint and largely illegible. It appears to be a continuation of a list or a detailed description of the items mentioned in the numbered list above.]













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The experimental determination of the performance of a capacitor-excited induction generator with an inductive reactance in series with the load.

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