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

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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

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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.

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

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.

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.

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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

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.

II. PROCEDURE

Prior to conducting the experimental work, the performance of the induction generating unit was analyzed[1*]. 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.

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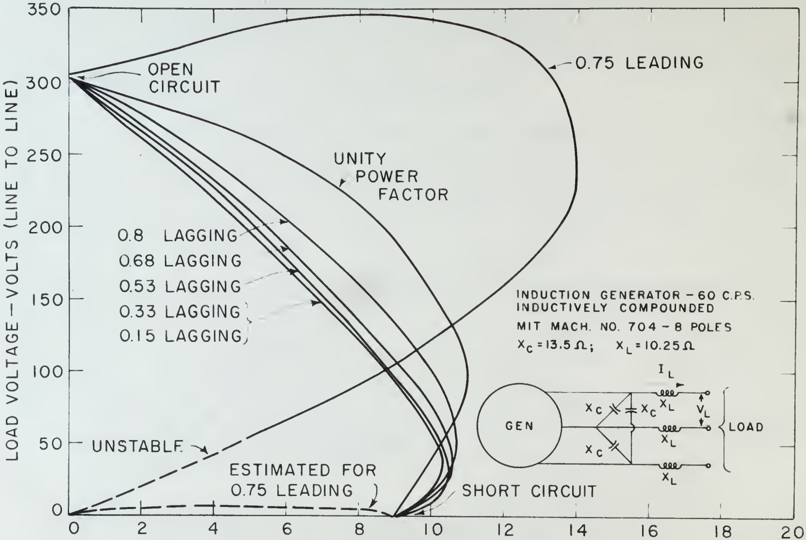
* Superscripts refer to references as listed in the Bibliography.

III. RESULTS AND DISCUSSION OF RESULTS

A. Steady State Characteristics

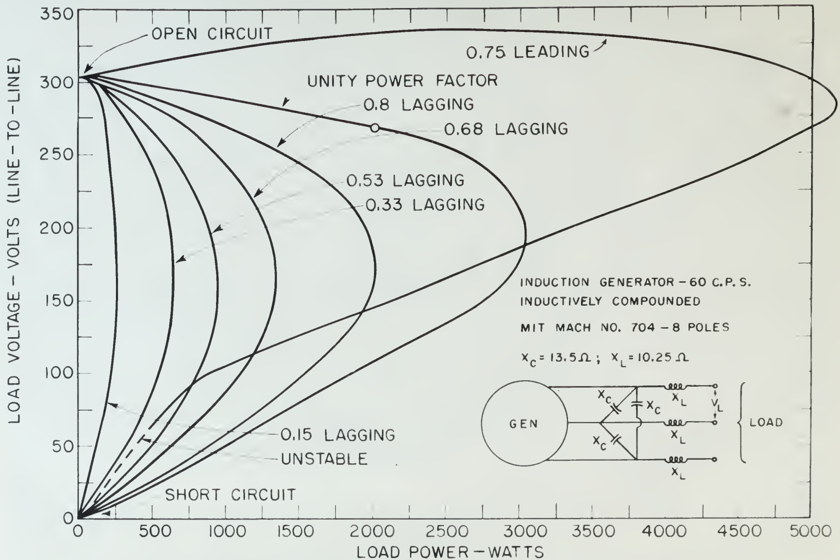
The analytical determination of the performance of an induction machine when driven above synchronous speed has been covered by Dr. Friauf[1] and verified by Swift[2] for both simple capacitor-excitation and for capacitor-excitation with capacitance compounding. Estes and Hussong[3] extended this work 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[1] 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.



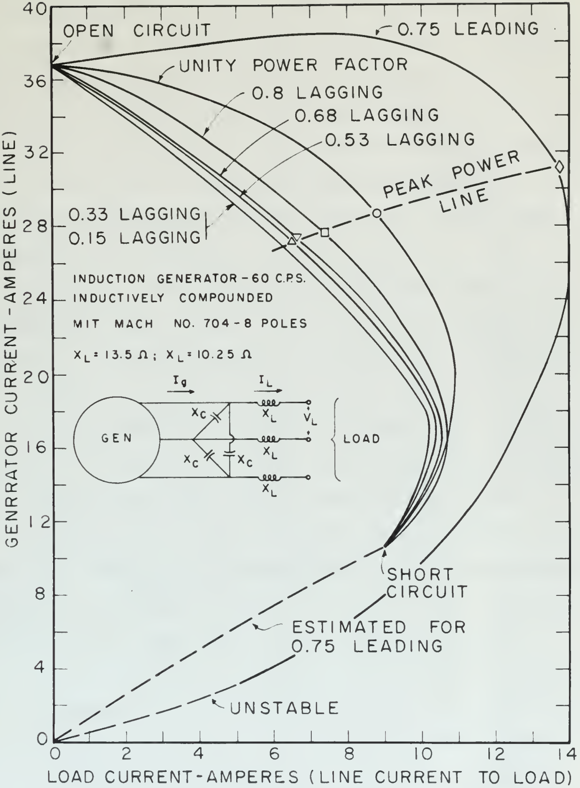
LOAD VOLTAGE VS. LOAD CURRENT FOR VARIOUS LOAD POWER FACTORS

FIGURE I



LOAD VOLTAGE VS LOAD POWER FOR VARIOUS LOAD POWER FACTORS

FIGURE 2



GENERATOR CURRENT VS LOAD CURRENT FOR VARIOUS LOAD POWER FACTORS

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 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[2] 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, Ig, 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.

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 machineis 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

$X_c = 13.5$	$X_L = 10.25$
Power Factor	Efficiency
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

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[3] 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 0.8 lagging power factor, at peak load is shown in figure 4. This waveform for the compounded generator was exactly similar to that obtained by Thessen[3] for the uncompounded case. This may also be observed on the oscillograms of transient behavior included in the following section of this thesis.

In order to extend the results indicated above, a series of runs, all at unity power factor but with various C_1 and X_C, have been plotted in figures 5, 6, and 7. On each figure the center curve (C_1 = 10.85, X_c = 17.3) is a duplication of the unity power factor curves of figures 1, 2, and 3 respectively.

A decrease in the value of C_1 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, in figure 5 with a 2.5 kw load, the improvement is from 15.0 percent to 6.8 percent. With a C_1 of 8.7 the generator would undoubtedly be operated at a higher power where its regulation would drop off. It is seen in figure 6 that the voltage characteristic is nearly linear until about 3.5 kw. It is further noted that the peak power available is considerably greater as C_1 is decreased.

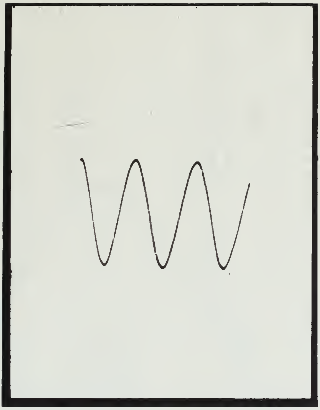
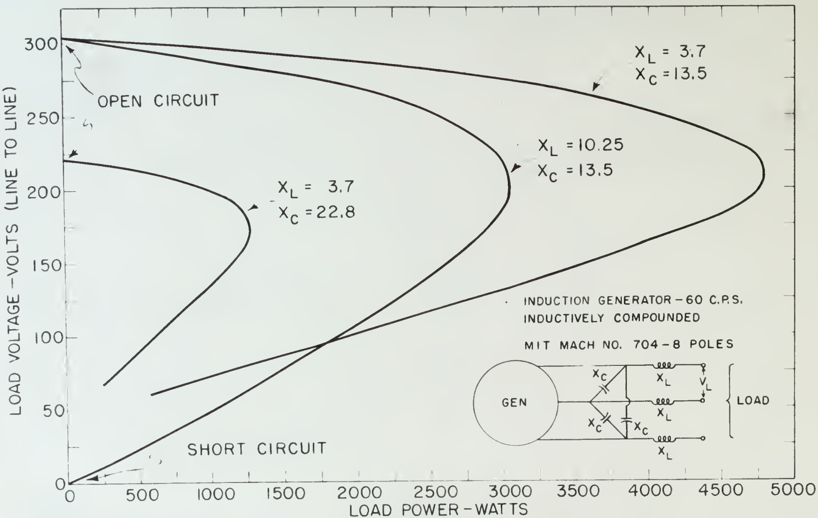


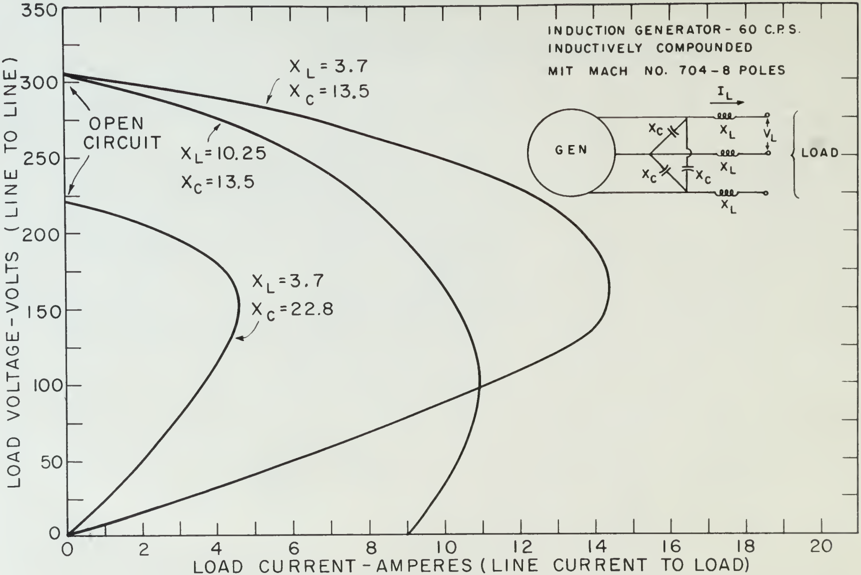
FIGURE 4

Voltage Waveform



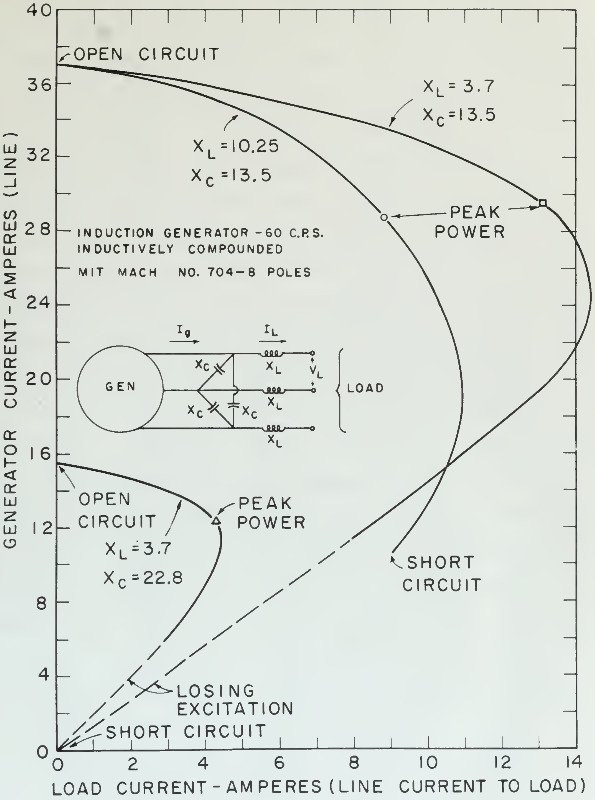
LOAD VOLTAGE VS LOAD POWER FOR UNITY LOAD POWER FACTOR WITH VARIOUS PARAMETERS

FIGURE 5



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

FIGURE 6



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

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

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

Parameters X_L	Parameters X_c	Efficiency
10.25	13.5	63.6
3.7	13.5	68.3
3.7	22.8	85.8

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[1] and checked experimentally by Swift[2]. 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.

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[3].

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 8. 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 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 8. The value used for shunt capacitance in all transient studies was one which provided an open-circuit voltage of 225 volts. With the capacitor selected, a reasonable power output of about 4.3 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, V_L of 8-a, obviously drops 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 then decays in an exponentially decreasing envelope. In approximately one-half second the short-circuit current is practically zero.

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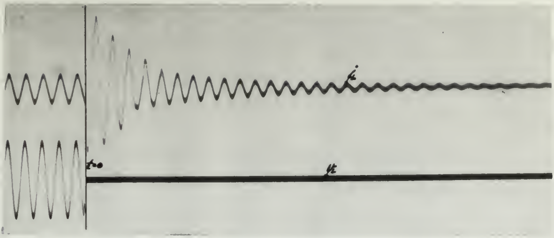
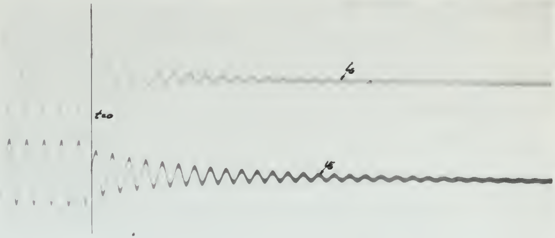
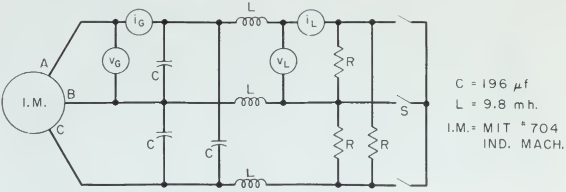


8-a. LINE TRANSIENTS



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.

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.

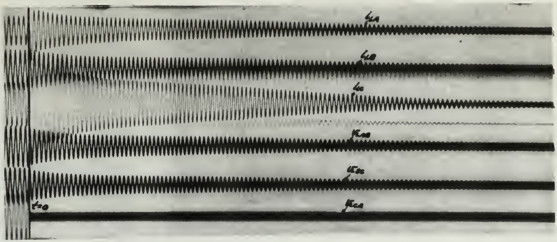
As in the previous case, with voltage, v_{Lca}, across the shorted phase going instantly to zero, the currents, i_{La} and i_{Lc}, in the shorted lines initially surge and thereafter exponentially decline to zero. Now, however, the rate of decay is nearly one-half that for the three-phase case. The maximum 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"

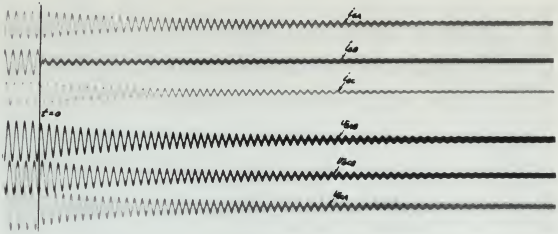
5.1 Single-Phase Short-Circuit - Of the two, the fault most commonly encountered is the single-phase, rather than a three-phase short-circuit. The transient effects of a single-phase short-circuit, as applied at the load terminals and machine terminals, are illustrated in the oscillograms of Figure 9-a 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, e_{ca}, across the shorted phase going instantly to zero, the currents, i_a and i_c, in the shorted lines initially surge and thereafter exponentially decline to zero. Here, 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.

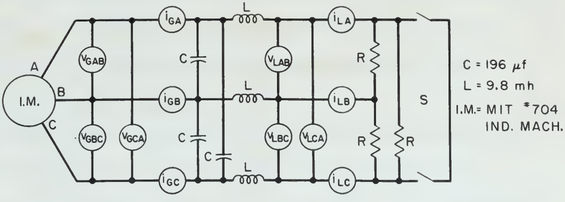
With voltage, e_{ca}, equal to zero, the instantaneous voltages, e_{ab} and e_{bc}, must remain equal in magnitude and separated by a 180-degree phase angle. A "quasi"



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 course of the upper oscillogram. This is attributed to a sticky reflection from one of the potential - recording galvanometers.

The oscillogram of Figure 9-c shows transients at the machine terminals and is similar in pattern to the corresponding oscillogram of Figure 9-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 9-c is evident in the trace for current, i_{cb}, of the latter. It was pointed out previously that the line currents, i_a and i_{cc}, momentarily rose 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.

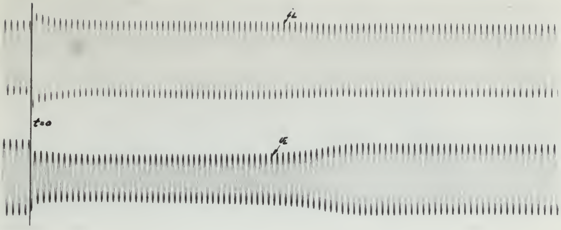
c.) Induction Motor Starting - To simulate a varying load demand on this power generating unit, several trials were made wherein the system load was suddenly increased or decreased. This section investigates the transient effects of suddenly starting an induction motor. Oscillograms obtained include 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 higher-than-normal values. In approaching the optimum values in the two phases, A and C, current is most rapidly drawn from phase B through the later-connecting capacitors. This causes a motor compensating drop in terminal current for the A-phase, as is shown in Figure 9-b.

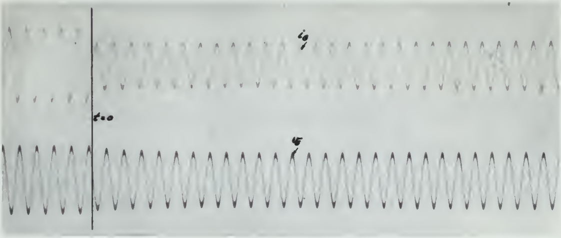
Power is eventually lost because, as explained in the discussion of a three-phase motor circuit, the capacitance seen by the induction machine is not sufficiently capacitive to furnish the necessary excitation current.

6.4 Induction Motor Starting. - To simulate a varying load demand on this power generation 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.

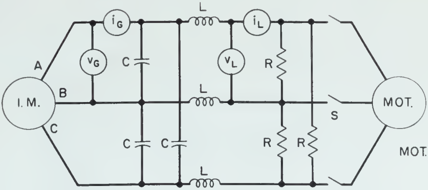
Figure 10 depicts traces of line current, i_L, and voltage, v_L, and machine current, i_M, and voltage, v_M. For the trial illustrated, there was a prior balanced load on the generator of about 4.4 kW before starting the induction motor. The induction motor was started and ran with a continuous shaft load equivalent to about 750 watts. From Figure 10-a it is seen that the line voltage initially dipped in agreement with commonly understood generating 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



10-a. LINE TRANSIENTS



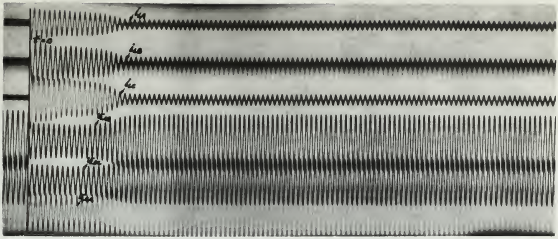
10-b. GENERATOR TRANSIENTS



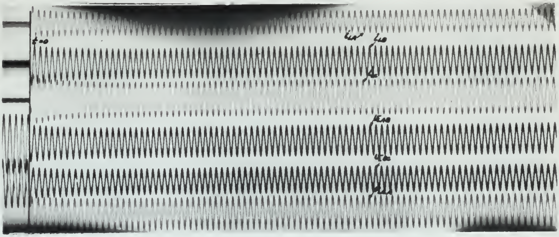
C = 196 μf.
L = 9.8 mh.
I. M. = MIT #704
IND. MACH.
MOT. = INDUCTION MOTOR
1 HP. 220V 3 φ

TRANSIENTS FOLLOWING INDUCTION MOTOR STARTING
WITH LOADED GENERATOR

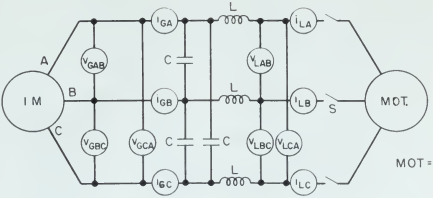
FIGURE 10



11 – a. LINE TRANSIENTS – LIGHTLY LOADED INDUCTION MOTOR



11 – b LINE TRANSIENTS – HEAVILY LOADED INDUCTION MOTOR



C = 196 μf.
L = 98 mh.
IM = MIT # 704 IND MACH

MOT = INDUCTION MOTOR 1 HP 230V 3 ϕ

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.

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[10].

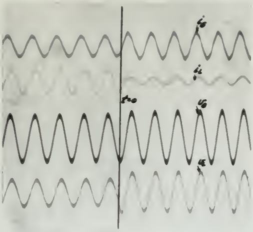
d.) Unloading - To complete the study of load variations on the induction generating unit, it was necessary to consider the effects of abrupt load removals. For this purpose the generating unit was loaded with parallel banks of resistors and then unloaded by cutting out resistance in three-phase sets. 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

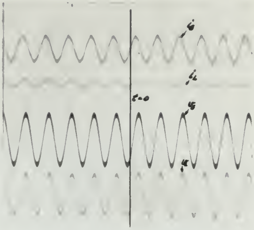
In neither case do the line transients show instantaneous values for current or voltage that might cause a generating unit casualty. In the latter case, the induction motor load was approximately one-fourth the maximum power output obtainable with the combination of capacitance and inductance used. As 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.[10]

4.4 Unloading - To complete the study of load variations on the induction generating unit, it was necessary to consider the effects of sudden load removals. For this purpose the generating unit was loaded with parallel banks of resistors and then unloaded by cutting out resistors in three-phase sets. Figure 11-4 illustrates both the line and the machine electrical transients following a sudden load reduction of 50 percent. The accompanying oscillogram of Figure 11-6 was obtained by dropping the remainder of the load.

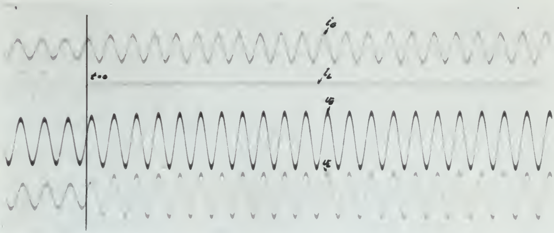
The traces of Figure 11-5 were recorded when the entire load was dropped in one step. In the first and third instances the initial load was approximately 3 kw. In all cases the load was symmetrical; thus, the effects in only one phase are illustrated. Again, in all three cases, the value of



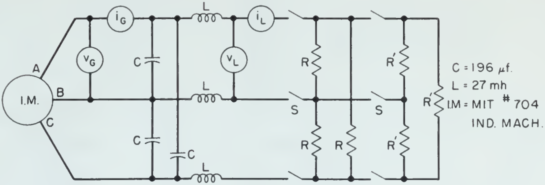
12-a. REMOVAL OF ONE HALF THE LOAD



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 consistantly 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 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 taken irregularity to preserve sinusoidal voltage output.

3.4 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 approximately 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.

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

[illegible]

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.

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

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.

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.

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.

VI. APPENDIX

A. DETAILED PROCEDURE

The method that Friauf[1] 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′)

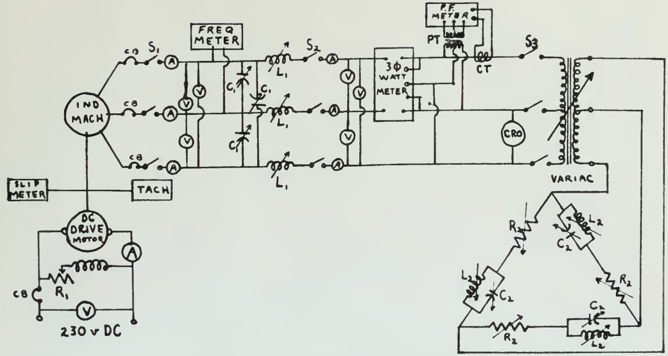


FIGURE A-1—CIRCUIT DIAGRAM FOR STEADY STATE OPERATION

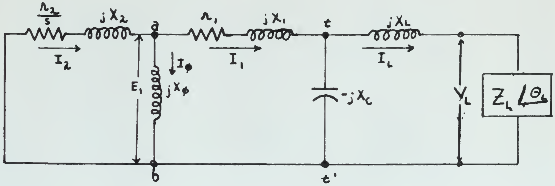
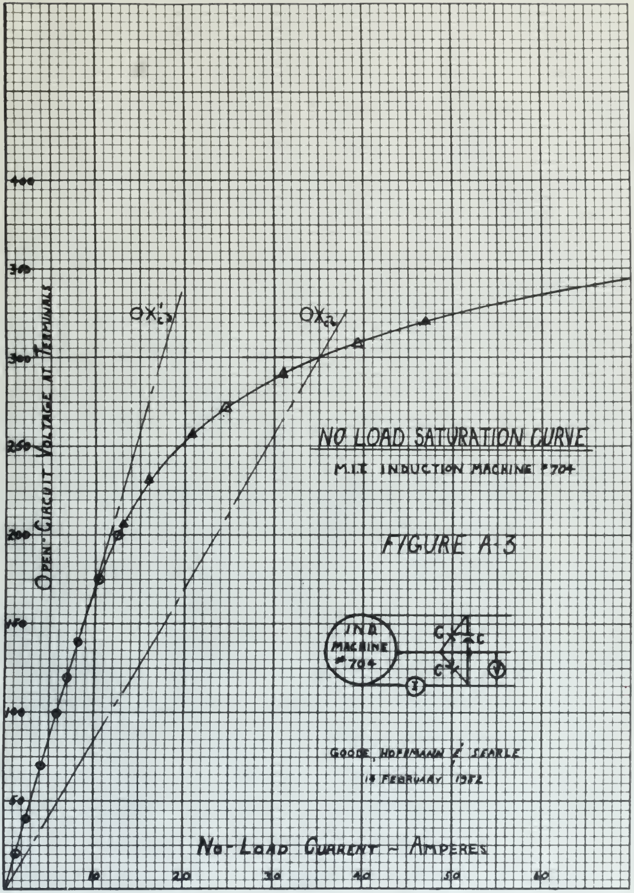


FIGURE A-2-EQUIVALENT CIRCUIT OF ONE PHASE


NO LOAD SATURATION CURVE
M.I.T. INDUCTION MACHINE #704
FIGURE A-3
IND MACHINE #704
C
C
C
V
I
GOODE, HOFFMANN & SEARLE
14 FEBRUARY 1952
OPEN-CIRCUIT VOLTAGE AT TERMINALS
NO-LOAD CURRENT ~ AMPERES
400
350
300
250
200
150
100
50
10
20
30
40
50
60

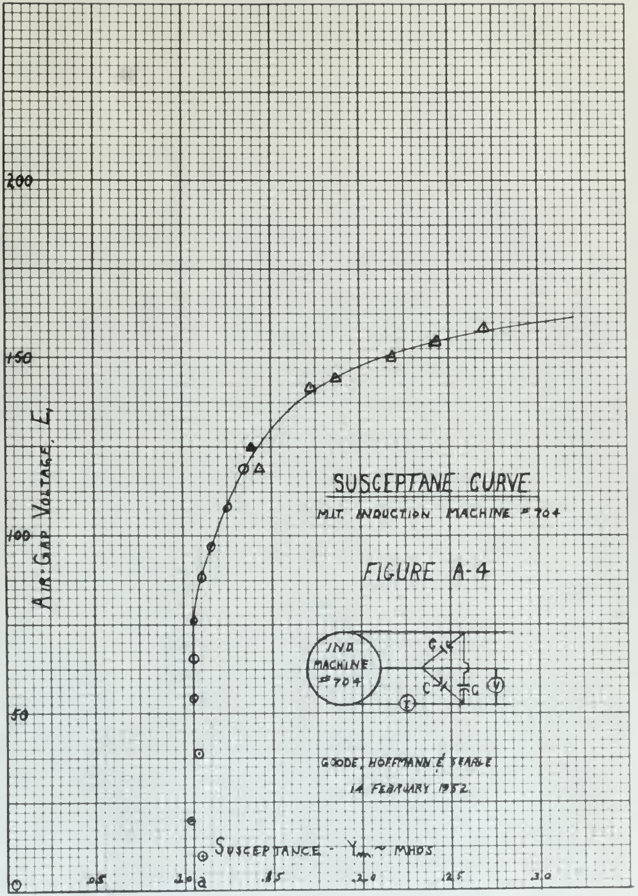
is essentially equal in magnitude to the magnetizing branch current, I_g. It will be noted that the slope of the straight line of Figure A-3, indicated by OX'_c, represents a critical value of capacitive reactance, below which the generator will fail to build up voltage. Open-circuit voltage is fixed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

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

Magnetizing susceptance, Y_ϕ, 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 existance of this minimum magnetizing susceptance is a direct consequence of the critical value of excitation reactance.


SUSCEPTANE CURVE
M.I.T. INDUCTION MACHINE #704
FIGURE A-4
IND. MACHINE #704
GOODE, HOFFMANN & SEARLE
14 FEBRUARY 1952
AIR-GAP VOLTAGE, E_1
SUSCEPTANCE - Y_m ~ MHOS
200
150
100
50
0
.05
.10
.15
.20
.25
.30

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

$$I_2 = I_\phi + I_1. \qquad (2)$$

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,

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

The admittances Y_2 and Y_1 may be expressed as:

$$Y_2 = \frac{1}{r_{2/S} + j\ x_2} \qquad (4)$$

and (5)

$$Y_1 = \left[r_1 + jx_1 + \frac{1}{\frac{1}{-jx_c} + \frac{1}{jx_3 + |Z|(\cos\phi + j\sin\phi)}}\right]^{-1}$$

An admittance diagram after the manner of Friauf[1] 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 rator constants of the machine as described elsewhere. From equation (4) 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:

$$\text{radius} = \frac{\frac{1}{2} X_c \frac{X_c}{X_c - X_3} \sec\phi}{\left(r_1 + \frac{1}{2} X_c \frac{X_c}{X_c - X_3} \tan\phi\right)^2 + \left[X_1 - \frac{1}{2} X_c\left(\frac{X_c - 2X_3}{X_c - X_3}\right)\right]^2 - \left(\frac{1}{2} X_c \frac{X_c \sec\phi}{X_c - X_3}\right)^2} \quad (6)$$

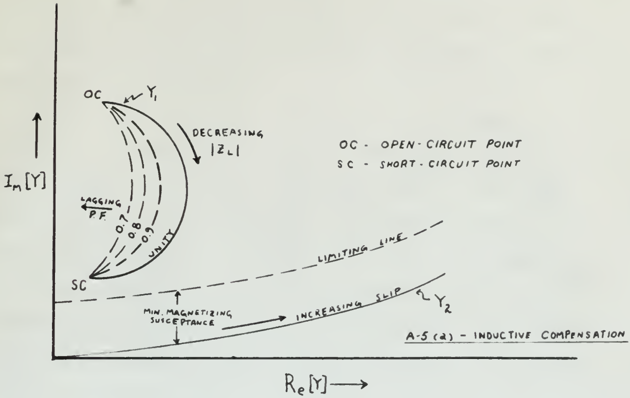
The center of the circle is located as the point having an abscissa of:

$$\frac{r_1 + \frac{1}{2} X_c \frac{X_c}{X_c - X_3} \tan\phi}{\text{(same denominator as Eq. 6)}} \quad (7)$$

and an ordinate of:

$$\frac{-X_1 + \frac{1}{2} X_c \frac{X_c - 2X_3}{X_c - X_3}}{\text{(same denominator as Eq. 6)}} \quad (8)$$

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 locii 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



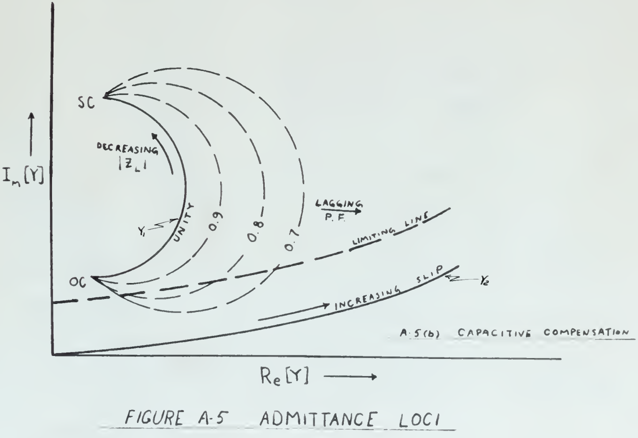


FIGURE A-5 ADMITTANCE LOCI

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_ϕ, 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[1] and experimental confirmation is included in the work by Swift[2]. 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,

Y_ϕ, 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 locii are similarly plotted for the case of an induction generator with capacitive, rather than inductive, compensation, two important changes occur. Locii 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.

TABLE A-I

Machine 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_ϕ = 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

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

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.

B. DATA

NAME 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			LOAD			Efficiency			
	V volts	I amps	P watts	V_g volts	I_g amps	s %	V_L volts	I_L amps	P_L watts	$\eta_{overall}$ %	η_{DC} %	η_{AC} %	I_g/I_L
Run I	221	12.2	2695	308	37.3	0.5	305	0	0				—
P.F. = 1.0	↓	17.8	3935	301	36.0	0.9	286	2.1	1055				17.1
X_L = 10.25		23.0	5080	295	35.2	1.7	269	4.5	2020				7.8
X_C = 13.50		27.4	6050	278	30.5	1.8	218	8.0	2990				3.8
	221	27.3	6040	271	28.7	1.6	194	8.8	3030	50.3	79.0	63.6	3.2
	222	21.6	4600	240	21.6	1.5	122	10.8	2250				2.0
	223	15.0	3350	217	17.5	1.2	76	10.8	1470				1.6
	220	5.2	—	163	10.6	0.9	0	(short circuit I = 9.0)					1.2
Run II													
P.F. = 0.8 lag	224	12.6	2820	305	36.8	0.3	305	0	0				—
X_L = 10.25	224	14.4	3230	303	36.1	0.6	289	1.3	480				27.8
X_C = 13.50	222	16.6	3720	297	34.9	0.9	272	2.4	980				14.5
	222	17.9	4010	294	34.0	0.9	257	3.1	1280				11.0
	223	19.3	4320	288	32.5	0.9	240	4.3	1600				7.6
	222	20.1	4500	279	29.8	1.0	207	6.0	1920				5.0
	223	20.2	4530	268	27.6	1.2	174	7.4	2020	44.7	79.0	56.5	3.7
	223	19.0	4250	260	24.7	1.3	140	8.8	1920				2.8
	223	16.6	3720	246	21.8	1.3	105	9.9	1600				2.2
	226	10.3	2310	219	16.4	0.9	47	10.7	650				1.5
	226	9.0	2015	199	14.1	0.9	27	10.4	520				1.4
Run III													
P.F. = 0.68 lag	226	13.6	2200	305	37.3	0.5	305	0	0				—
X_L = 10.25	↓	14.3	3070	300	35.6	0.6	289	—	370				—
X_C = 13.50		15.2	3230	297	34.3	0.7	269	2.4	760				14.3
		15.6	3440	287	32.6	0.8	242	3.5	995				9.3
		12.6	3520	274	27.4	0.8	171	6.6	1330	37.8	78.0	48.5	4.2
		9.8	2850	246	20.6	0.9	83	9.8	959				2.1
	226	13.6	2200	219	16.5	0.9	31	10.6	388				1.6
Run IV													
P.F. = 0.53 lag	—	—	—	305	37.3	0.5	305	0	0				—
X_L = 10.25	226	13.0	2940	299	35.4	0.6	285	0.87	330				40.7
X_C = 13.50	↓	13.6	3070	293	32.9	0.6	251	2.8	640				11.8
		13.6	3070	276	27.3	0.6	166	6.5	950	31.0	77.0	40.5	4.2
		12.2	2750	258	22.5	0.6	102	8.8	810				2.6
	226	10.4	2350	237	18.7	0.6	55	10.2	530				1.8

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

	D.C. Motor			Generator			Load			Efficiency			I_g/I_L
	V	I	P	V_g	I_g	s	V_L	I_L	R	$\eta_{overall}$	η_{DC}	η_{AC}	
	volts	amps	watts	volts	amps	%	volts	amps	watts	%	%	%	—
Run V	226	11.5	2600	305	36.6	0.7	305	0	0				—
P.F. = 0.33 lag	↓	12.1	2730	304	36.0	0.6	302	—	144				—
X_L = 10.25		12.4	2800	303	30.3	0.6	218	4.1	580				7.4
X_C = 13.50		12.1	2730	288	27.8	0.7	183	5.6	650				5.0
		11.7	2640	282	25.6	0.8	152	6.9	660	25.0	74.5	33.6	3.7
		11.1	2510	272	23.2	0.7	123	8.1	610				2.9
		10.4	2360	256	21.1	0.7	93	9.2	530				2.3
		9.6	2030	222	17.7	0.9	54	10.2	350				1.7
	226	4.8	1085	128	10.1	1.0	0	(short circuit I = 8.9)					1.1
Run VI	224	11.7	2620	305	36.5	0.6	305	0	0				—
P.F. = 0.15 lag	224	12.4	2780	305	35.8	0.4	299	—	144				—
X_L = 10.25	226	11.6	2620	286	33.2	0.5	261	2.3	192				14.4
X_C = 13.50	225	10.8	2430	278	30.2	0.6	217	4.1	240				7.4
	226	10.4	2350	271	28.2	0.6	185	5.5	256				5.2
	225	9.8	2200	261	25.2	0.7	142	7.4	258	11.7	70.5	16.6	3.4
	226	9.0	2040	251	21.6	0.6	99	8.9	218				2.4
	225	7.4	1660	231	15.9	0.6	40	10.3	88				1.5
	227	3.8	860	155	10.0	1.1	0	(short circuit I = 8.8)					1.1
Run VII	224	12.05	2700	305	36.3	0.4	304	0	0				—
P.F. = 0.75 lead	224	25.4	5660	301	38.2	1.0	337	5.0	2160				7.6
X_L = 10.25	224	36.8	8180	293	38.1	1.5	345	8.8	3900				4.3
X_C = 13.50	220	45.1	9910	258	31.3	2.6	283	13.7	5160				2.3
	223	34.2	7640	226	25.0	2.4	227	14.0	4080	53.5	78.9	68.0	1.8
	225	27.9	6240	209	22.1	2.8	200	13.4	3360				1.6
	225	5.0	1125	85	4.0	3.2	61	5.8	480				0.7

DATA

Steady - State Characteristics

All runs at 60 c.p.s.

	D.C. Motor			Generator			Load			Efficiency			
	V	I	P	V_g	I_g	s	V_L	I_L	R	$\eta_{overall}$	η_{DC}	η_{AC}	I_g/I_L
	volts	amps	watts	volts	amps	%	volts	amps	watts	%	%	%	—
Run V	226	11.5	2600	305	36.6	0.7	305	0	0				—
P.F. = 0.33 lag	↓	12.1	2730	304	36.0	0.6	302	—	144				—
X_L = 10.25		12.4	2800	303	30.3	0.6	218	4.1	580				7.4
X_c = 13.50		12.1	2730	288	27.8	0.7	183	5.6	650				5.0
		11.7	2640	282	25.6	0.8	152	6.9	660	25.0	74.5	33.6	3.7
		11.1	2510	272	23.2	0.7	123	8.1	610				2.9
		10.4	2360	256	21.1	0.7	93	9.2	530				2.3
		9.6	2030	222	17.7	0.9	54	10.2	350				1.7
	226	4.8	1085	128	10.1	1.0	0	(short circuit I = 8.9)					1.1
Run VI	224	11.7	2620	305	36.5	0.6	305	0	0				—
P.F. = 0.15 lag	224	12.4	2780	305	35.8	0.4	299	—	144				—
X_L = 10.25	226	11.6	2620	286	33.2	0.5	261	2.3	192				14.4
X_c = 13.50	225	10.8	2430	278	30.2	0.6	217	4.1	240				7.4
	226	10.4	2350	271	28.2	0.6	185	5.5	256				5.2
	225	9.8	2200	261	25.2	0.7	142	7.4	258	11.7	70.5	16.6	3.4
	226	9.0	2040	251	21.6	0.6	99	8.9	218				2.4
	225	7.4	1660	231	15.9	0.6	40	10.3	88				1.5
	227	3.8	860	155	10.0	1.1	0	(short circuit I = 8.8)					1.1
Run VII	224	12.05	2700	305	36.3	0.4	304	0	0				—
P.F. = 0.75 lead	224	25.4	5660	301	38.2	1.0	337	5.0	2160				7.6
X_L = 10.25	224	36.8	8180	293	38.1	1.5	345	8.8	3900				4.3
X_c = 13.50	220	45.1	9910	258	31.3	2.6	283	13.7	5160				2.3
	223	34.2	7640	226	25.0	2.4	227	14.0	4080	53.5	78.9	68.0	1.8
	225	27.9	6240	209	22.1	2.8	200	13.4	3360				1.6
	225	5.0	1125	85	4.0	3.2	61	5.8	480				0.7

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

	D.C. Motor			Generator			Load			Efficiency			
	V	I	P	V_g	I_g	s	V_L	I_L	P_L	$\eta_{overall}$	η_{DC}	η_{AC}	I_g/I_L
	volts	amps	watts	volts	amps	%	volts	amps	watts	%	%	%	—
Run VIII	224	11.6	2600	306	37.1	0.5	305	0	0				—
P.F. = 1.0	224	8.2	4080	300	35.7	1.0	295	2.5	1210				14.3
X_L = 3.7	223	24.3	5410	295	35.3	1.4	283	4.9	2340				7.2
X_C = 13.5	222	31.5	7000	286	34.1	1.8	266	7.9	3520				4.3
	↓	35.3	7840	278	32.8	2.0	249	9.6	4100				3.4
		40.7	9040	255	28.5	2.7	212	13.1	4800	53.1	78.0	68.3	2.3
		27.4	6080	190	21.5	3.5	137	14.0	3220				1.5
	222	17.4	3860	148	16.7	3.8	104	11.4	2060				1.4
	224	8.4	1890	99	11.3	4.4	68	7.9	890				1.4
Run IX													
P.F. = 1.0	224	4.1	916	221	15.4	0.3	220	0	0				—
X_L = 3.7	↓	5.2	1153	216	15.2	0.5	218	—	238				—
X_C = 22.8		6.4	1433	213	14.9	0.7	213	1.0	493				14.9
		7.6	1700	206	14.5	0.8	207	2.3	812				6.3
		8.8	1970	196	13.8	1.0	196	3.0	1080				4.5
		9.4	2120	173	12.4	1.5	171	4.3	1270	59.8	69.5	85.8	2.9
		7.5	1680	139	10.3	2.0	136	4.4	1030				2.3
		5.6	1255	111	8.6	3.1	108	3.6	696				2.4
	224	3.8	862	80	6.1	3.2	82	3.2	416				1.9

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

DATA

Transients

1. Three Phase Short Circuit
   c = 196 mf - L = 9.8 mh

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

2. Single Phase Short Circuit
   c = 196 mf - L = 9.8 mh

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

3. Starting Induction Motor - With Loaded Generator
   c = 196 mf - L = 9.8 mh

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

After Transient: P_L = 4.1 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 mf - L = 9.8 mh

Before Transient:

V_g = 300 volts

I_g = 34 amps

V_L = 300 volts

I_L = 0

f = 60 c.p.s.

After Transient: P_L = 600 watts

Induction Motor Data as directly above.

5. Unloading
c = 196 mf - L = 27 mh

Full Load:

V_g = 265 volts

I_g = 27 amps

V_L = 188 volts

I_L = 8.4 amps

P_L = 2700 watts

f = 60 c.p.s.

Half Load:

V_g = 294 volts

I_g = 34 amps

V_L = 280 volts

I_L = 3.0 amps

P_L = 1440 watts

f = 60 c.p.s.

BIBLIOGRAPHY

1. J. B. Friauf, "Calculation of Capacitor-Excited Induction Generator Performance", Unpublished. 23 June 1948, (Notes at Code 650, Bureau of Ships, Navy Department, Washington, D. C.)

2. C. S. Swift, "An Investigation of Capacitor-Excited Induction Generator Performance and a Verification of a Method of Performance Calculation", Annapolis, Md., 1950. (Thesis at U. S. Naval Postgraduate School, Monterey, California.)

3. O. T. Estes and W. J. Hussong, Jr., "Study of Capacitor-Excited Induction Generators; Parallel Operation and Transient Loading", Cambridge, Mass., 1951. (Thesis at Massachusetts Institute of Technology.

4. A. S. MacAllister, "Excitation of Asynchronous Generators by means of Static Condensers", ELECTRICAL WORLD AND ENGINEERS, Vol. 41, 17 January 1902.

5. A. S. MacAllister, "Asynchronous Generators", AMERICAN ELECTRICIAN, Vol. 15, November 1903.

6. Stanley and Faccioli, "A-C Machinery - Induction Alternators", Trans. AIEE, Vol. 24, 1905.

7. Hobart and Knowlton, "The Squirrel-Cage Induction Generator", Trans. AIEE, Vol. 31, Part II, 1912.

8. D. F. Alexander, "The Polyphase Induction Generator", THE ELECTRIC JOURNAL, Vol. 25, 1928.

9. F. O. Stebbins, "Effects of Capacitors and Varied Voltages Upon Induction Motor Characteristics", G. E. REVIEW, April 1934.

10. Basset and Porter, "Capacitive Excitation for Induction Generators", Trans. AIEE, Vol. 54, May 1935.

11. Kurtz and Corcoran "Introduction to Electric Transients", John Wiley and Sons, New York, 1935.

12. H. P. Hoya, "Self Excitation of Induction Generators", Cambridge, Mass., 1938. (Thesis at Massachusetts Institute of Technology.)

13. C. F. Wagner, "Self Excitation of Induction Motors", Trans. AIEE, Vol. 58, 1939.

14. C. F. Wagner, "Self Excitation of Induction Motors with Series Capacitors". Trans. AIEE, Supplement Vol. 60, 1941.

15. "Self Exciting Alternator", ENGINEERING, Vol. 168, October 21, 1949.

16. O. J. M. Smith, "Generator Rating of Induction Motors", Trans. AIEE, Vol. 69, 1950.

17. M. Walker, "Asynchronous Generators; Simple Theory Without Mathematical Complication", ELECTRICAL REVIEW, Vol. 147, November 1950.

18. H. H. Roth, "Induction Generators for Small Loads", POWER, Vol. 94, December 1950.

19. Tsao and Tsang, "Squirrel Cage Induction Generator for Power Generation". AIEE Misc. Paper 51-158, ELECTRICAL ENGINEERING, Vol. 70, September 1951.