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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.

Lalbary

U. S. Naval Postgraduate Schoo! Monterey, California





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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Richard William Goode, Lieutenant, U. S. Coast Guard Henry Acker Hoffmann, Lieutenant Junior Grade, U. S. Navy Willard Franklyn Searle, Jr., Lieutenant, U. S. Navy

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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 the second of a second second

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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. Departicle, mastacommets they in, 1952

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#### 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. V

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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 in mount winch

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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. compensation will result and power presention is ansured for all levelop moves factor loads.

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#### II. PROCEDURE

Prior to conducting the experimental work, the prime I\* formance of the induction generating unit was analyzed. 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. 3.

<sup>\*</sup> Superscripts refer to references as listed in the Bibliography.

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#### 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.

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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\_ 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.

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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, 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. 9

10. It is most important to note have take the loss of excitation accurate will there take power and the realized with the power build-op as may the take does include by addy<sup>2</sup> for the convectation-conversion generator. This is, df depres, here we have and the information is, df depres, here we have an infident with a semicure (finable X<sub>0</sub> and X<sub>1</sub>) are and any to an arbitration (finable X<sub>0</sub> and X<sub>1</sub>) are not interport to an arbitration antil well after the spectrum that. This is much in detail in the investion.

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A cross curve of peak power is shown in Figure 3. This has no significance other than perhaps predicting the load current and the  $I_1$  to  $I_\alpha$  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  $I_{\rm L}$  to  $I_{\rm c}$  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.

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Efficiency at Maximu for Various Load	Im Power Condition 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

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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 opencircuit 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 quice linear until about 3.5 KW. It is further noted that the peak power available is considerably greater as  $X_t$  is decreased.

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Voltage Waveform







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







15.



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

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The results show on Figure 7 Inducate that for a given generator mether, the retir of ined current to purpose correct is activer as the value of " is terrecond. This of treaty would again inch and it warned initiar quarking afficiency for the site of terrecond with a provide would be powerted that the measuring-set settime for the result is another by the construction of the results of resting of the mether of the initian results of the resting of the mether of the measuring to the setting of resting of the mether of the measuring the results of resting of the mether of the measure of the results of the resting of the mether of the measure of the results of the resting of the mether of the measure of the measure of the resting of the rest of the mether of the measure of the measure of the rest of the measure of the mether of the measure of the measure of the rest of the measure of the mether of the measure of the measure of the rest of the measure of the mether of the measure of the measure of the rest of the measure of the mether of the measure of the measure of the rest of the measure of the mether of the measure of the measure of the measure of the terms of the mether of the measure of the measure of the measure of the terms of the mether of the measure of the measure of the measure of the terms of the measure of the measure of the measure of the measure of the terms of the measure of the m 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		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<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:

 Continuous generation for all lagging power factors is assured if excitation is continuous for unity power factor. 17.

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2.	0.25	7.5

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- In cases of leading or lagging power factor, where discontinuity of excitation exists, the discontinuity occurs after the peak power condition.
- 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>.

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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.) Drawsiant SourceCircle of a name interact of the load constrains and in the generator to stain resulting inter a three-phase contracteral, are literinfed to be an amplifugrame of Figure 5. Do while men for their stain and the direct values of 22 value men mitch provided in dynaotrect values of 22 value. Not the interact of establish a reasonable phone when it that 4.3 27 we obtained a reasonable phone when it that 4.3 27 we obtained was 50 c.p.s. Team (the interact of the share was 50 c.p.s. Theory (the interaction of the share be referred to as a clice will).

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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, ig, and voltage, eg, 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 shortcircuited 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, ig, there appears an initial surge of directcurrent, followed by an exponential decay to zero. As a result, the entire exponential envelope of the sinusoidallyvarying 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.

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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 tracerecorded 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 threephase 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"

1.1 Instalations Supervised 1 - Of the two, the fault more evenually encountered is the Electrophase, rather than a three-phase electrolical. The investor effects all a single-phase electrolical, as evaluation at the load terminals and machine bound-circuit, is evaluation at the load oscillograms of Figure 9-e and Figure (-a, respectively, these k or phase C. Mawyer, all three under these phase k or phase C. Mawyer, all three under these recorded and, obviously, the conditions of share k wave are adusted to had voltiges in all three maintance and mass adusted to had voltiges in all three maintance and oscillograms and the investors in all three maintance and isother attained. Note that the pare selectore and acting man and and the investors of investors and oscillogram and the investor of an investor oscillogram and a start of the investors of and and the startes of the investor of a start isother and a startes of the investors of a start isother and a startes of a startes of a start isother and an antistic of investors of a start isother and an antistic of investors of a start isother and an antistic of investors of a start isother and a startes of the investors of a start isother and a startes of a startes of a start isother and an antistic of investors of a start isother and a startes of a starting and a start and isother and a startes of a starting and a start and a startes of a startes of a starting a startes of a start isother and a startes of a starting a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a start isother and a startes of a startes of a startes of a start isother and a startes of a startes of a start isother and a star

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9-a LINE 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 guickly 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  $i_{rc}$ , momentarily surged to 24

trace is suparent in the connect of the upper coniliogram. This is estributed to a many collection from one of the potential - reconding polyameters.

The saciilogram of Figure 9-o shows framelents of the machine strates on the state of the contract pording osc ilogram of Thirty on the the the manner shore circuit. Ino no ewareny difference a land homever. The first is manifested by the doublest this al decary in atreman mith condictone Line Line, a monthile emination of this may be tound as completely the transland valtanes sample the tage short rapiditors. Mich the three plane cherr diract, there unparticles are each shunted through a sorter in working, the voltage across the consellers divisitions recipies on same. On the other hand, in the instance of a nele-phase sorting, only use concitor is shunted through series in actings. It would be expected that the veltages worss the other two coordings would have a lange spuring oright ha long as these volumes are suchabled, the induction mething will appeirs succession partons. It is inter ante puter destruction will not completely our i michty in start all three phases are whorted.

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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 Algense chairmainei voisse. Is notree the obtach werget is the beer states, i am 5, mergens is new readily down from phase 5 through the inter-personal or readily down. This source a matter requirefair itse in evolve total componentses can be requirefair itse in evolve tot.

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10-b. GENERATOR TRANSIENTS



TRANSIENTS FOLLOWING INDUCTION MOTOR STARTING WITH LOADED GENERATOR FIGURE IO







TRANSIENTS FOLLOWING INDUCTION MOTOR STARTING WITH UNLOADED GENERATOR FIGURE II

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 ll-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.
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At the machine terminals, cherene and entrage vary as indicated by the traces of flows 15%. We can be mean, slightly different tool treatmention terminics in the run dorthe which this satisface was reconsist. The techney for terminal writige is remain an entry contains is ewely due to the high degree of secretarian in truck the actine has both members. The states every is the institute a dorease is evolvation current as the institute are dithe balantas presented of its andress and the institute the balantas presented of the andress was pre-

The next the set is pressed to articleurs of fairs they showing the affects in the line of an investion motol bally started with an utbasked semeration unit. The oscillogram presented in Figure 11-0 is far a similar condition except that here the induction estim are movily invest.

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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>.

<u>d.) Unloading</u> - 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 matther same do the line transmitte show incriminants values for currence or valiance tait might donne a memorial and countries. In the increase stall, the formulation vector lease are appropriately monocarry the maximum power output discount as the motor-mattering in maximum power output made. As the motor-manufally will lease evolution inductional induction matching approximation is intriner increased, the induction matching approximation is intriner increased, the sentences, as in the shart directly case, on damperous termements as outputs avaid to promote. In comparison, the induction matching current in which or non-starting an induction matches with a symplectic rease, no damperous terments are sentence of the starting and the starting and induction matches of the start and a starting an induction the power current of the starter and active times the power current of the starter and active

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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 (in 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

shuft conscience was the same as for all previous transfert linvating tions, Hommer, the volue of the regime inductance was increased schemac in order to give pror volvage regulation between the unlowled and the londed somelizons. By doing this, it could be sepected that voltage serve, if it existed, would be demonstrated mate tiearly. An examination of the thread oscillograms a own that he voltige with courses. The line voltage Lostonionursly juma to a value numrly equal to the new standy-sinks wills. The residuing shall increase in voltage is caralined gradually in the maxt quarter of a second. The converted voltage realing hearly constant; the mail chines involved is consisted within S cycles. Upon decreasing the Lond by one-walf, the line ourrent (1: of signer 18-a) swithing a remerkanic training to effect. It appears that interest is an extremely ever-largest nathers.

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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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#### IV. CONCLUSIONS

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

- The no-load characteristics of this generating unit are determined by the exciting capacitance and machine constants.
- With load applied, the line voltage regulation is improved as series inductance is reduced, holding shunt capacitance constant.
- 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.
- 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.

## TV. COUNTERPORT

For work performed with the self-owelzed induction generator marks instation compounding lands to the following some industry

- The ne-load characteristics of this generation whit are decomined by the exciting depactance and merilie conserves.
- Mith load spplies, the line voltage regulation is improved as sains loadequice is reduced, heiding source capacitance capacitance.
  - b. With constant surface limitstance, the live solvage regulation is improved by raising the same symmitty.
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these of power use to institution memorizing industries over not accur butode the penaruling with here aristrane mostere power antalarnis with a given semination of transitioned and constitutes.

- 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.

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

- Efficiency of the permeting unit is poor for partial loads muy to the presence of a large exclusion current.
- The translation (allowing fourty and output, issue changes to not produce encessive excrements or potentials in the concentraunit or line. Insurved short-curvelt extreme is forecome area the relative values of sector insurvement area.

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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.

any last or dimension and prime generation, but vite all not actual before rescaling the mater of minimum power. Purthermones, and equally impresses, inductive values that ised to this solution to dimension, inductive values that maximum densitients with a site of very matrice area. In the leads, mathem inductions and be several to zero, i.e., no enveryoritients and the even of the several of zero, i.e., and the leads then are inductions and the regularmation of brown attacks are not real powers regulartion to brown attack where on the several devenue rise leads the state of the several state regulartion of brown attacks where on the several devenue rise leads the several state of the several state of the real leads.

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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.

Four rolling regulations is one of the major dismivariages of the induction memorance without commensation. Static commension improves volvers reminister, og: introduces singenesites may be a sufficient solution. For Adjustable compensation may be a sufficient solution. For blide purpose, capacities may be a sufficient would not be accepted to a sufficient of the static term would not be accepted because supplies, de the state bank, an adjustation at present, intelate, de the state bank, an adjustation inductione could be continuously increased to the bas desired into values content existing.

One servers that industry prostation involves and of an eutometically runnacided in industry and a server and of an in ited increases, if a volver provide a server additionstand by destroating are induction trapping a voculatory applier. The inductive restances by br indultakey a substation open reserver, or a menetic the induction of the difference in it is built that out paired in mendius of the induction presenter has been paired in mention of the induction presenter has been paired in mention of the induction presenter has been paired in mention of the induction presenter has been paired in mention of the indiction presenter has been paired in mention of the indiction of the second action in the stary of viewpoint.

The advantance of induction parameter will targen more apparent it tidher frequenties. The and mast of connectanoous could then an continuently recorded, plane the best tendent-even while with some leaded with high conce spece. For these related is 11 is researched which furnish more an partnement of will upper. Frequency regulation should also be investigated with a view toward reducing the frequency transient following changes in load demand. For practical use in a turbogenerator 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 redesigning 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.

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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 )

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The wathod this intra- developed for performants calculations was modified to include the error of inductive responding and thim employed to prover values for shart inpactions for series incotence for interatory work. A qualificative description of vale analytics, wer follow.

by realized warmerian in the risk which and structure to invite a souther as in the start of the sector as the sector as cesselfaner, a no-load arthmation curve was obtained and out of the support of anapped has allermentances realization of this curve, police man outside by connecting the Liberton sections through a surface to a 200-yeally lockers many the local part that firms parts or about Linderses to eaching a to come of rectained and white relates. Sale in the block-saliton eacher and to purply about the said character bed forer-sublications is no I've be all will be a will be placed by but with therease



### FIGURE A-I-OIRCUIT DIAGRAM FOR STEADY STATE OPERATION



FIGURE A-2 - EQUIVALENT CIRCUIT OF ONE PHASE





is essentially equal in magnitude to the magnetizing branch current,  $I_{\rm g}$ . It will be noted that the slope of the straight line of Figure A-3, indicated by  $OX'_{\rm c}$ , 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,  $OX_{\rm c}$ , 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<sub>1</sub>, 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:

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

Magnetizing susceptance,  $Y_{p}$ , 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. is essentially areal in magnitude to be emperially branch courrent, 1. It will be noted that the slope of the struight line or sigure set, indicated by  $M_{c}^{-}$ , represents a tribled value of constitive restance, below which the guarantic will fail to build up voltage. Open-struits without he straight the intermetion of the saturation surve with the straight line,  $M_{c}$ , the slope of which is streed by now value of shurt constitute.

Knowing the machine constants, the state impedance dood was calculated for various values of no-ized sectorion current. By subtracting vectorily, these impedance doops from the corresponding terminal voltages on a pot phase basis, values of siz-gap valtage, F, ware determined.

It was assumed that there are no resistance included in the magnetizing scanne. The enscriptions of the magnetizing branch can then be expressed by the relations

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

$$I_2 = I_p + I_1^{\circ}$$
 (2)

which may be expressed as:

 $E_1 Y_2 = E_1 Y_4 + E_1 Y_1.$ 

 $Y_2$  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.

$$Y_{p} = Im \left[Y_{1}\right] - Im \left[Y_{2}\right]$$
(3)

The admittances Y2 and Y1 may be expressed as:

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

and

$$1 = \left[x_{i} + j x_{i} + \frac{i}{j x_{i}} + \frac{i}{j x_{i} + |z| (\cos \phi + j \sin \phi)}\right]^{2}$$

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 rator constants of the machine as described elsewhere. From equation (4) it is seen that for a given Meterring was to the equivalent direct of Figure (-2, Kirrhoff's success equalion epiled to for paint a, will result in the exception:

which may be arrested as:

 $V_{\rm I}$  is the addition enclose to the left of paints a - b;  $V_{\rm I}$  is the antitunes excludely to the sight of paints a - 1; and Y is the additiones of the magnetizing branch.

Rearranging terms and employing the assumption of purely reactive impedance in the expecticing branch, the fluel desired expression for meminicaling subservice is,

$$(v_1 - v_2 [v_1] - v_2 [v_2]) = 13)$$

The Admittances Ye and Y may be expressed as:

(b) 
$$\frac{1}{2^{n-1} + p_0^2} = q^2$$

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$$V_{\pm} = \frac{1}{2^{n_1+1}x_{+}^{n_2+1}} \frac{1}{2^{n_1+1}} + \frac{1}{2^{n_1+1}}$$

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then propired showing the local of "1 one vy on a complete plane. First, it was undersary to determine excention taily the stator and secur constance of the minipuo is unsertied also direct. From wantatoo (4) (4 to seen our 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:

$$IS = \frac{\frac{1}{2} \chi_{c} \frac{\chi_{c}}{\chi_{c} - \chi_{3}} \sec p^{\prime}}{\left(\kappa_{i} + \frac{1}{2} \chi_{c} \frac{\chi_{c}}{\chi_{c} - \chi_{3}} \left(\zeta_{a,c} p^{\prime}\right)^{2} + \left[\chi_{i} - \frac{1}{2} \chi_{c} \left(\frac{\chi_{c} - 2\chi_{3}}{\chi_{c} - \chi_{3}}\right)^{2} - \left(\frac{1}{2} \chi_{c} \frac{\chi_{c} \sec p^{\prime}}{\chi_{c} - \chi_{3}}\right)^{2} - (\zeta_{a,c})^{2}}$$
(6)

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

$$\frac{x_{c} + \frac{1}{c} x_{c} \frac{x_{c}}{x_{c} - x_{3}} \tan \varphi}{(\text{same denominator as Eq. 6})}$$
(7)

and an ordinate of:

radi

$$\frac{-x_1 + \frac{1}{2}x_2 - \frac{x_2 - 2x_3}{x_2 - x_3}}{(\text{same denominator as Eq. 6})}$$
(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 locil of  $Y_1$ . The centers of these circles move to the left as the load power factor decreases. It circles pass through the open-circuit point and the short-circuit point, because for load impedance marking, by the motion tradition of size, which along up a spectral har, the Lower of by and plotted as fullifiered in plotted ar-rist.

It can be address that the locus of admittance V1, also magnitude of lock insidence, 11, us a personniar, is a sizele for a pirmo satitud when anoth acquisitence, sation industance, and local power factor insis are all held emotion. The realist can be moreated by:

$$\frac{\frac{1}{2}\chi_{k}}{\left(\alpha_{i}^{+} + \frac{1}{2}\chi_{k}^{-} \frac{\chi_{k}}{\chi_{k}^{-}}, \xi \circ \cdot \cdot \rho\right)^{2} + \left[\chi_{i}^{-} + \chi_{k}^{-} \chi_{k}^{-} \chi_{k}^{-} \right]^{2} - \left(\frac{1}{2}\chi_{k}^{-} \chi_{k}^{-} \chi_{k}^{-}\right)^{2} - \frac{1}{2}\chi_{k}^{-} \chi_{k}^{-} \chi$$

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$$\frac{z_{\sigma} - x_{\sigma}^{2} \lambda_{\sigma} \frac{z_{\sigma}}{z_{\sigma} - y_{\sigma}} \frac{\partial x_{\sigma}}{\partial x_{\sigma}} \frac{\partial x_{\sigma}}{\partial x$$

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man a sizela inco one of to donn in these books. Labolad only noose (as on, to the loss of openant insite the vertex to plue languag power (normer, i thally of elements in these for her presidence of by, the same sector of these sizelies one to the large on the interpretation of these sizelies of elements the large of the interpretadet base interference where the sector of the interpreta-


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,

moust to initially or zero, power (actor is accolupions. An broader out mariiver, the open-circuit point is fixed by the value of share separatrance. The shout-circuit point fails balow the open-circuit point and moved namity vertically up or down with intreacting or decreduated series induceance respectively.

Even equilien (2) is is seen that megneticing missentimes,  $Y_{\phi}$ , is equal to the variised distance (now the force of  $Y_{2}$  or the iccus of  $Y_{1}$ . A straight distance (now the force analysis of the performance of the instruction parameter may be commoned at this point. In belof, the method introdives prophically pication off Values of memorizing methods for melacet values of analitations,  $Y_{1}$ . Then, unsets inter for melacet values of analitations,  $Y_{1}$ . Then, we ta make of the susceptions of analitations,  $Y_{1}$ . Then, introdives prophically pication of analitations,  $Y_{1}$ . Then, use to interval to analitation of analitations, veltage. Having a value for ani-app voltage and a correspondtion value of admitication of insets eiterpit ind value of admitication  $Y_{1}$ , application of insets eiterpit analysis will load to saturd to associated of analysis.  $W_{1}$ , and is a correspond.  $T_{1}$ , of the september of analysis,  $W_{2}$ , and load correspond.  $T_{1}$ , of the september of the sector  $W_{2}$ .

The nector of partoners advantation is toud is the nector of Dr. Talast<sup>2</sup> and experimental continuition is included by its each is subt<sup>2</sup>. For this conth the method second is encoded, subt<sup>2</sup>. For this conth is the action second restriction on a monthale for this of making second and performing the include for atomsective incompany second to the incut of a second that as the second of monthale for an active that as the second of monthale for a second  $Y_{\phi}$ , 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 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.F. standards. The values of machine constants so obtained are listed in Table A-1.

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### TABLE A-I

Machine Constants for M.I.T. Induction Machine No. 704

rl	-	0.43 ohms
<b>r</b> 2	#	0.174 ohms
×1	8	0.58 ohms
x2	=	0.58 ohms
×ø	æ	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<sub>1</sub>, 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

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avoid of		4	8.9

A value of shark constitute and shifted high main give an approvised anti-out and anterphysic a safe very limit. A value or contact industries was then determined which would becare the there-alcedic coine name, or shown inductions that an industries of expections and dispeter. Figure 4-1, was one on. The bolocian mailine was conserved as an exprised marked and an an allow all of -c union. Speed was more of an annually regime the generators of the solution of the structure the generators of the solution of the structure the generators of the solution of the structure the generators of the the solution of the structure the generators of the solution of the structure the generators of the solution of the structure of the constructure of the solution of the structure of the structure the generators of the solution of the structure of the structure the generators of the solution of the structure of the structure the generators of the solution of the structure of th

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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<sub>3</sub> with its secondary connected to provide singleand 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

from .15 largeles to .76 locality by idjointing the local instance with  $l_{21} \in \mathbb{Z}_{22}$  and  $l_{22}$ . The dark employees to reason to the tensor but the dark dependent (but the dark level) and the plotters in Figures 1, 2, 4 and 3.

Purther investigation are constrained with the possibility of improving voltage resultion by decreasing the value of series inductions, i.e. stark (for VIII, the sum value of short resolutions, Cr. was sume of in the provinge rest. toom (sum 72), to decreased, while is resulted at the rest value of Cr was decreased, while is resulted at the induct solution. These rund ware made at with the with presented and, for example on, are protected with the with presented to result of hum 1. The pute soperator in the Account is plotted in figures , c. we're operator in the the work, and is

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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<sub>2</sub> 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. alree the assady state appearing before the interruption
is a 60 cycle trace which can be used for theing. To
accompilat medden application of ican, a 1 mt. three-phase
induction motor was stated under load by connecting it
three(h is "pullieting" switch. For unlokelr character
latics, The value of 1, was increased as a stor function
by using a maister from the sized.

Dain complied for ine transform elever are locked in the appendix and restlic frame are shown in flyinger 0 - 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	. 488464	5 St	yle 89C120
7.5 HP	220 volts	60 CP	S 3 ph	ase
Poles	4	Ū	£	12
Amps per Terminal	19.7	19.3	25.3	33.8
Full load RPM	1710	1130	860	570
Temperature rise 5	00 in one	hour at	100 per	cent load.

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55.

### Transients

Three Phase Short Circuit 1. c = 196 mf - L = 9.8 mhBefore Transient:  $V_{c} = 255 \text{ volts}$  $I_{g} = 29 \text{ amps}$  $V_{I} = 212 \text{ volts}$  $I_1 = 13 \text{ amps}$  $P_{\rm T} = 4.8 \, {\rm KW}$ f = 60 c.p.s. 2, Single Phase Short Circuit c = 196 mf - L = 9.8 mhV = 255 volts Before Transient:  $I_{cl} = 29 \text{ amps}$  $V_r = 212 \text{ volts}$  $I_{r} = 13 \text{ amps}$ P. = 4.8 KW f = 60 c.p.s. 3. Starting Induction Motor - With Loaded Generator c = 196 mf - L = 9.8 mhBefore Transient:  $V_{g} = 260 \text{ volts}$ 28 amps I<sub>q</sub> =  $V_{r} = 218$  volts I = 11 amps  $P_1 = 4.4 \text{ KW}$ f = 60 c.p.s.

### Transformat.

- Inter Maan Short Clenks 10 8.9 = 1 - 1m 601 = 3 1.0 ad low com 1 30 mar. 22 1 V. - Dil volte ages 61. · .... 17 N.h = .9 10 - . p. S. = 5 S. Single Make Sadet Clically un ul - 1 - 1m del = a ailey Ch - W. Refere Transferts anna RS = # V e 1 1.3 more 10 0.4 ÷ /1 starting induction while - this holded impressed
  - the state of the s

After Transient: P. = 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 mhBefore Transient:  $V_{cr} = 300$  volts  $I_{cr} = 34 \text{ amps}$  $V_I = 300 \text{ volts}$ I; = 0 f = 60 c.p.s. After Transient:  $P_{\tau} = 600$  watts Induction Motor Data as directly above. 5. Unloading c = 196 mf - L = 27 mhFull Load:  $V_{\alpha} = 265 \text{ volts}$  $I_{\alpha} = 27 \text{ amps}$  $V_T = 188 \text{ volts}$ I. = 8.4 amps  $P_T = 2700 \text{ watts}$ f = 60 c.p.s.  $V_{a} = 294$  volts Half Load:  $I_{c} = 34 \text{ amps}$ Vr = 280 volts  $I_T = 3.0 \text{ amps}$  $P_{\rm I} = 1440$  watts f = 60 c.p.s.

57.

After Frankland: 1 - 6.0 KD

Indiction Mater Ustat

1 h... 220 v. 3 phase

4. Exacting induction for  $c=0.1\,\mathrm{m}^{11}$  with adda there are a 0.1

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