AN EXPERIMENTAL INVESTIGATION OF SELF-EXCITATION ON 60-CYCLE, SINGLE-PHASE POWER CIRCUITS

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in partial fulfillment of the requirements
for the degree of
DOCTOR OF PHILOSOPHY
May, 1965

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ACKNOWLEDGMENTS

Indebtedness is acknowledged to Dr. William L. Hughes, chairman of my committee, for his valuable guidance and advice during the composition and fulfillment of my graduate program. It was through his help that I received the Forgivable Loan from the Ford Foundation, which made this program financially possible. I wish to express a most sincere thanks to Professor Claude M. Summers, my thesis adviser, whose intense interest in the thesis subject and suggestions during the investigation made possible the completion of the project.

An expression of appreciation is extended to the members of my committee, Professor Jeanne Agnew, Professor John B. West, and Professor Paul McCollum for their encouragement and prompt consideration. Mrs. Barbara Adams, who typed this thesis, is also due an expression of thanks for her promptness and diligence.

I would also like to express my deepest appreciation to my wife, Nadine, whose patience, understanding, and encouragement helped make my complete doctoral program a success.

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CHAPTER I

INTRODUCTION

A necessary condition for the satisfactory operation of an electrical power system is that the service voltage be maintained within acceptable limits. Since most of our electrical energy conversion devices (commonly called "loads" by the electrical power distribution engineer) are designed to operate on a reasonably constant voltage, they do not perform satisfactorily on low or high voltage. For example, the life expectancy of an incandescent lamp is seriously shortened by high voltage, whereas its output or illumination is reduced by low voltage. Compressor motors sometimes will not develop sufficient starting torque on low voltage.

Load growth on a distribution circuit may be recognized as an increase in line current. An increase in line current must be accompanied by a corresponding drop in customer voltage due to the inductive voltage drop incurred by the load current as it passes through such circuit components as generators, conductors, transformers, regulators, and motors. Even though power may not always be desired by the customer, energizing currents must flow through the primary circuit so that the customer will always have power available at his command.

Two of the most important and difficult problems faced by the distribution engineer are those of voltage regulation and light flicker. Voltage regulation of a transmission or distribution line is defined as the rise in voltage at the receiving end, expressed in per cent of full-load voltage, when full load at a specified power factor is removed while the sending-end voltage is held constant. Expressed in equation form, it is

$$\text{Per Cent Regulation} = \frac{|V_{NL}| - |V_{FL}|}{|V_{FL}|} \times 100$$

where $|V_{NL}|$ = magnitude of receiving-end voltage at no load

$|V_{FL}|$ = magnitude of receiving-end voltage at full load

Therefore, zero per cent is recognized as good regulation, whereas fifty per cent is not good regulation on a constant-voltage system.

Light flicker is caused by the sudden voltage drop as a result of an inrush of current required by some large electrical load such as the starting of a motor or the sudden switching of an electric furnace.

Unlike the previously mentioned inductive loads, the excitation current of a capacitor leads the voltage across its terminals and causes the power factor to be low and leading. The capacitor, therefore, provides a tool for the distribution engineer to correct lagging power factor produced by inductive loads, increase system capacity, provide better voltage regulation, and, in the case of series-connected capacitors, reduce instantaneous voltage fluctuations which cause light flicker. The operation of both shunt-connected and series-connected capacitors is described in the next chapter of this investigation.

Even though the series application of capacitors can provide automatic voltage regulation in cases of instantaneous and load cycling voltage fluctuations, it may under certain conditions produce instabilities which may prove detrimental to the operation of the power system. Two of these instabilities are often referred to as "ferroresonance" and "self-excitation."

Any series circuit containing a capacitor and a saturable reactor or transformer of certain kva rating may develop ferroresonance, a condition of very-high currents and voltages. This condition on low-frequency power circuits may be audibly detected by the increase in sound level issuing from the reactor or transformer. The large currents produced may cause certain protective devices to operate which could lead to an undesirable discontinuity of service. Overvoltage may also puncture the insulation of cables and electrical equipment and cause costly damage, as well as interruption of service. The subject of ferroresonance is discussed in Chapter III.

An instability called self-excitation (a condition less frequently observed than ferroresonance) may also exist in a series circuit containing a capacitor, transformer, and motor. This phenomena may be observed in power circuits of low frequency by the lack of smoothness of motor operation and sometimes by the motor failing to attain its rated speed. Large currents also flow under this condition. The greater portion of this investigation centers around self-excitation and is discussed in Chapter IV.

Seldom do these instabilities occur in series-capacitor applications; but when they do, they occur with such severity that the series application of capacitors has not been utilized to its fullest potential. Chapter V is devoted to the description and operation of certain protective devices which are designed to extinguish self-excitation and ferroresonance and to reduce the severity of these two conditions.

The objectives of this thesis are:

1. To obtain self-excitation and ferroresonance on a single-phase, 60-cycle circuit in the laboratory.
2. To try to devise some reasonably simple way to predict the performance of such a system.
3. To investigate and see if another way exists of extinguishing the high currents brought on by ferroresonance and self-excitation.
4. To indicate what direction to take for further investigation of the subject.

The writer cannot hope to obtain a complete solution to such non-linear, multivariable problems as ferroresonance and self-excitation; but it is hoped that after this work is complete the problems may be better understood by following investigators as well as by the writer.

One other point should be made clear. The phenomena known and referred to as ferroresonance does not always have to be detrimental to all circuits but can be utilized to great benefit in certain other types of energy conversion areas.

CHAPTER II

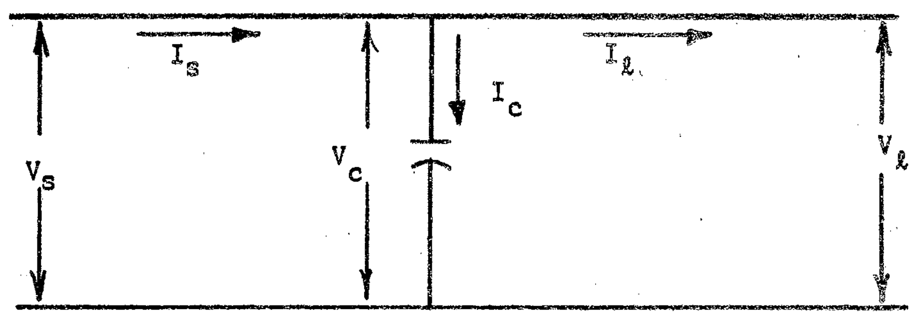
SERIES CAPACITORS

The commercially produced power capacitors are normally rated in kvar and kv. They may be connected in a power circuit in any way which does not exceed the recommended operating limits. Generally, they are connected either across the line (shunt) or directly in the line (series).

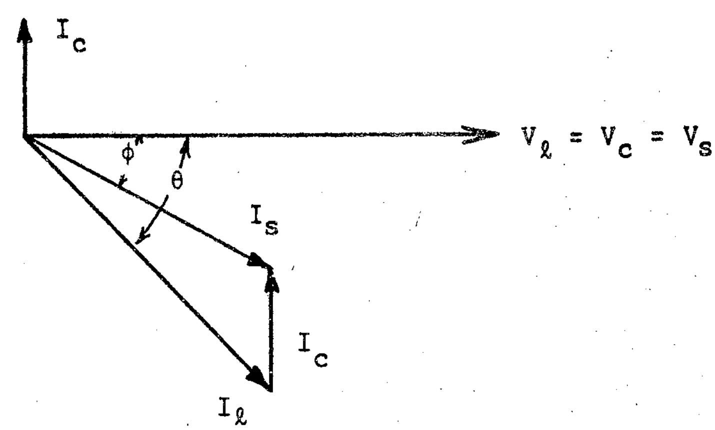
A capacitor when shunt connected draws a constant current whose magnitude depends on the capacitor size measured in kvar and the voltage to which the terminals are connected. The benefits obtained from this type of operation have appeared many times in the literature; and the three most important are improved voltage regulation, improved power factor, and increased system capacity (1).

Since the method of application is the criteria for determining whether a capacitor is series or shunt, two additional benefits are obtained if the capacitor is connected in series. One of these is automatic voltage regulation. The voltage developed across the series capacitor is proportional to the load current and, therefore, increases as the current increases.

Figure 2.1A illustrates the circuit of a shunt-connected capacitor. The source voltage V_s, capacitor voltage V_c, and load voltage V_ℓ are all common to the circuit and are chosen as the reference phasor in Figure 2.1B. The load current I_ℓ is shown inductive in the phasor



A. Circuit Diagram for Shunt-Connected Capacitor



B. Phasor Diagram for Shunt-Connected Capacitors

Figure 2.1

diagram and lags the voltage by an angle θ degrees. The current through the capacitor I_c is purely capacitive and leads the voltage by 90°. The source current I_s is the vector sum of I_c and I_ℓ and is shown to be lagging the voltage by an angle ϕ. The current carried by the feeder from the source to the capacitor terminals has been reduced and, consequently, so has the IX_L drop and the line loss.

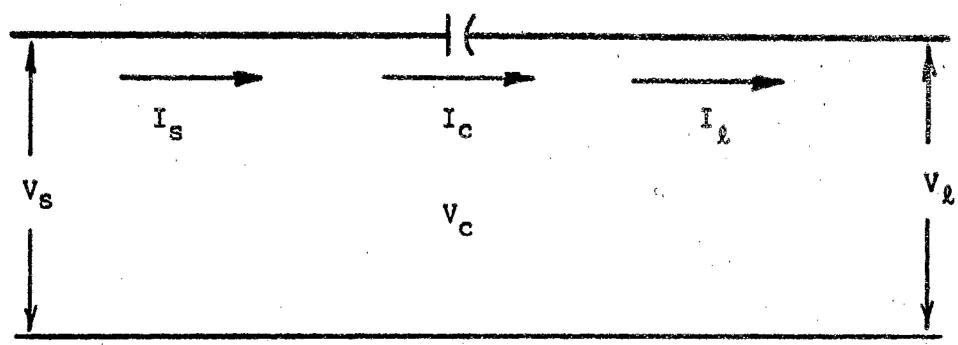
A series-capacitor application is shown in Figure 2.2A. The current is common to all elements in this circuit configuration and is used as the reference in the phasor diagram of Figure 2.2B. Here the capacitor voltage is

$$V_c = I_\ell X_c$$

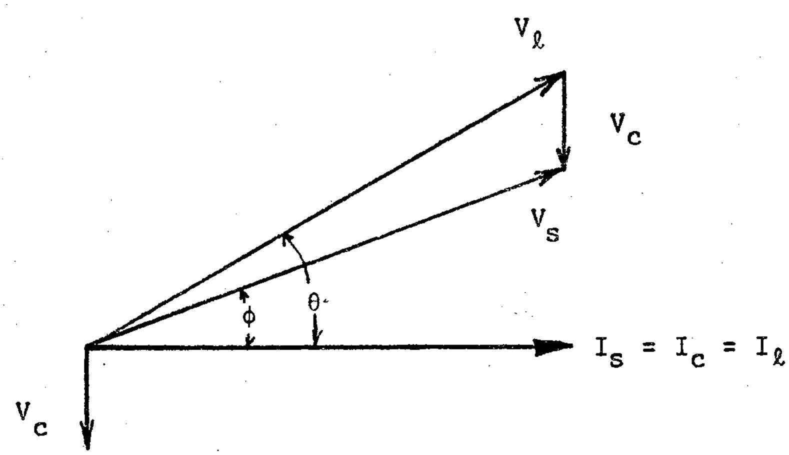
where X_c = capacitive reactance

and is the vector difference between the source voltage and load voltage. The source power factor has been improved as can be seen from the phasor diagram.

The second additional benefit produced by the series capacitor is that of reducing the instantaneous voltage fluctuations produced by motor starting and the cycling of other high-inrush current loads. Large-inrush currents, whether cyclically repeated or nonrepetitious in nature, sometimes cause the load voltage to suddenly drop. The magnitude of such a drop causes associated lighting loads to be affected to the extent that a perceivable change in light output is noticed. This is commonly called "light flicker" and becomes quite bothersome at times. The mechanics of how the capacitor functions to reduce the voltage fluctuation and indirectly the light flicker can be found in



A. Circuit Diagram for Series-Connected Capacitors



B. Phasor Diagram for Series-Connected Capacitors

Figure 2.2

the literature (2-5). Some electric utilities for years have been reducing the voltage fluctuations producing light flicker by connecting a capacitor in series with the ground bushing of the single-phase distribution transformer supplying the load. With the growth of central air conditioning and the use of large, single-phase electric motors to drive the units, the light-flicker problem has increased in magnitude and frequency on circuits which tend to become long and overloaded. Other differences between shunt- and series-capacitor applications have been presented and will not be considered as significant to this problem (6).

Besides the advantages offered by series-capacitor application are several disadvantages. The series capacitor should be provided with some type of shunting device to insure against capacitor overvoltage and ultimate failure in the event of a fault on the system involving the capacitor. If this protection is not provided, the capacitor may fail and cause severe damage as well as interruption of service. Some types and the operation of the shunting device are discussed in detail later in this work.

Another disadvantage of the series capacitor is that for certain values of circuit parameters it tends to cause the circuit to become unstable. Since such large magnitudes of power are transmitted by power distribution circuits, any element of the circuit possessing the capability of becoming unstable is carefully studied; and its usefulness to the circuit is sometimes sacrificed to avoid a potentially unstable condition.

CHAPTER III

FERRORESONANCE

Description and General Discussion

Although ferroresonance was not the prime objective of this investigation, the writer feels that some consideration should be given to this phenomenon. The circuit configuration which was used lends itself to this condition, which was experienced numerous times through the investigation.

Some circuit arrangements containing saturable reactance, resistance, and capacitance, when excited with certain magnitudes of driving voltage, will produce large, circulating currents accompanied by very large voltages across the reactive elements of the circuit. The currents produced in a series arrangement of capacitance, saturable inductance, and resistance can be classified into three types.

The first type may be called steady-state sinusoidal. It is the current which flows in the circuit when the inductor is operating in the low-current portion of its characteristic. This is the condition found in the steady-state excitation of transformers and is the desirable circuit condition in the operation of power systems.

The next two classes of currents occur in the nonlinear section and above the knee of the transformer saturation curve. It has been shown by McCrumm (15) that a series arrangement of capacitance, nonlinear inductance, and resistance may produce subharmonic currents of the second, third, sixth, and ninth order. These harmonics were obtained by suddenly energizing the circuit by switching the voltage rather than slowly increasing the magnitude of voltage already applied. It was also shown by McCrumm that there appeared to be regions on a volt-ampere characteristic plot that could be classified as regions subject to subharmonic currents and other regions which would produce only transient currents. The transient currents have been observed by the writer in both a high-voltage circuit (7,200 volts) as well as in a low-voltage circuit (110 volts) and appear to have no perceivable harmonic associated with them. They have waveforms which are highly distorted and are very large in magnitude.

Many definitions of ferroresonance have been given, but ferroresonance is generally associated with large, steady-state currents which circulate in a circuit containing capacitance and a saturable reactor or transformer. Most circuits subject to ferroresonance do have several stable operating points. Some change in any one of the circuit parameters, or driving voltage may cause the current to move from an operating point of high currents and voltages to another point characterized by low currents and voltages. This movement from one stable state of operation to another and then possibly back to the original state is generally referred to as the "jump phenomena" of ferroresonance. One of the earliest recorded reports of the ferroresonance jump phenomena in the United States was that of H. B. Dwight and C. W. Baker (7). Since then, various articles have appeared which either attempted to explain the condition analytically or graphically or to fix the operating limits (8-20).

Since ferroresonance depends on the nonlinear characteristic of the saturable reactor or transformer (whose inductance is a function of the current), analytical solutions are very difficult to obtain. The circuit equations are nonlinear, integro-differential equations which are further complicated by the many variables involved, since ferroresonance can be influenced by the circuit parameters, loading conditions, and driving voltage.

Butler and Concordia (9) were able with the aid of a differential analyzer to solve the circuit equations of some particular circuit configurations and establish limits of normal excitation as a function of shunting resistance and capacitive reactance. The equations leading to the analyzer solution were of the form

$$E \sin (\omega t + \beta) = i_1 r_1 + L \frac{di}{dt} + \frac{d\psi}{dt} + \frac{1}{C} \int (i_1 - i_2)\, dt \qquad (3.1)$$

$$i_2 r_s = \frac{1}{C} \int (i_1 - i_2)\, dt \qquad (3.2)$$

where ψ = flux linkage

β = phase angle of applied voltage

i_1, i_2 = loop currents

C = capacitance

L = inductance

E = maximum voltage applied to circuit

$\omega = 2\pi f$

f = frequency

The above equations are those of the circuit shown in Figure 3.1. It was found that the magnitude and the wave shape of the current could be controlled to a great extent by the variation of the series resistance, shunt resistance, capacitance, leakage flux, flux linkages, driving voltage, or the combination of two or more of these.

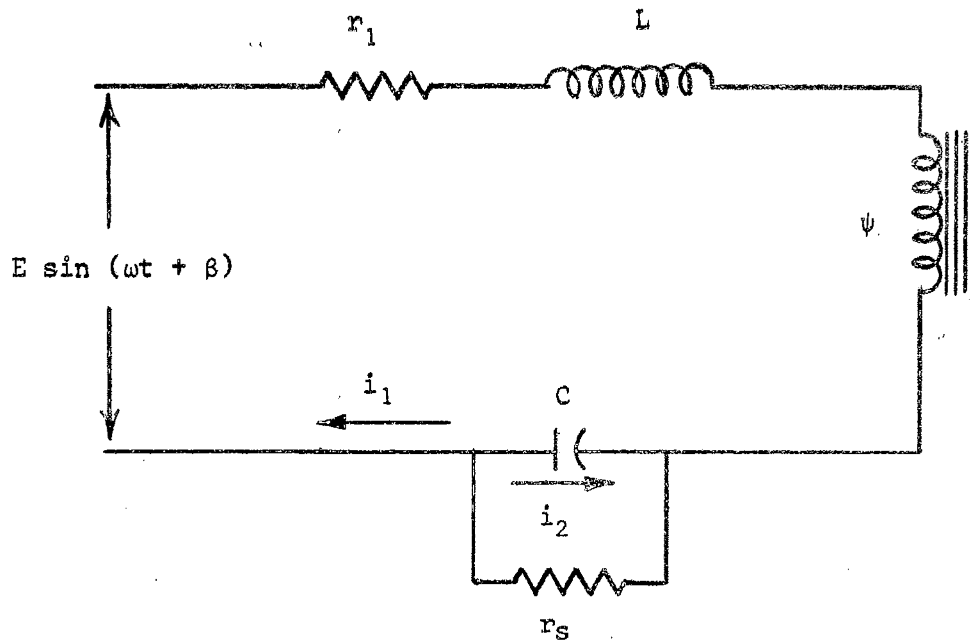


Figure 3.1. Series Circuit with Capacitor Shunting Resistor

A later investigation by Kratz, Manning, and Maxwell (18) revealed that the point on the voltage wave at which the circuit was energized had a major effect on obtaining ferroresonance. They also concluded, with the aid of an analog computer, that the polarity and magnitude of the transformer residual magnetism had a definite effect on the occurrence of ferroresonance at closing angles near 90 degrees.

Although the writer had no means of setting and determining the magnitude and polarity of the residual flux, it was observed that a circuit which would not ordinarily go into ferroresonance when the voltage applied was slowly increased in magnitude, would go into ferroresonance if the voltage was set at a certain value and switched onto the circuit. The severity of the ferroresonant currents depended on the magnitude of the voltage and the circuit parameters.

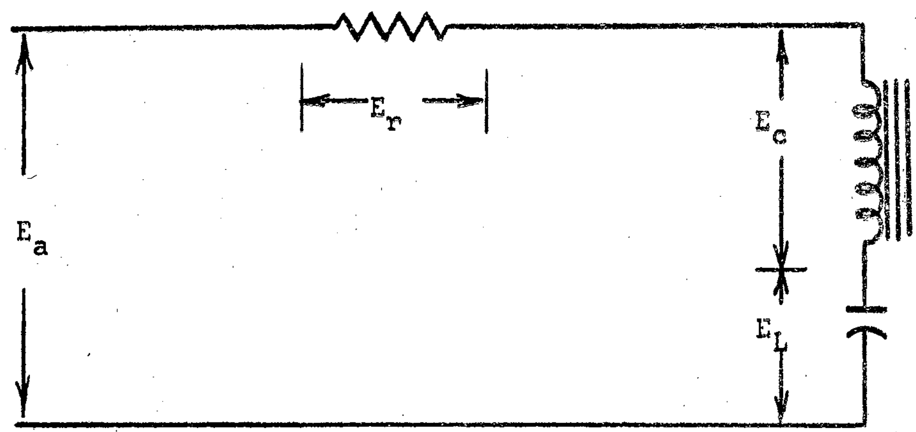
The reactive elements of the circuit shown in Figure 3.2A have volt-ampere characteristics similar to those in Figure 3.2B. The curve labeled E_L is commonly called the saturation curve of a saturable reactor or transformer and is characterized by three portions. The first is the line segment from 0 to a and can be considered as fairly linear. Its slope is large and depends on the materials from which the core is made. The section from a to b is referred to as the "knee" of the saturation curve and is quite nonlinear. The section from b to c is again fairly linear, and its slope is dependent on the flux leakage path; since any operation of the transformer in this region is with the core well saturated. Transformers with different grades of core material will have different slopes in the linear portions, but all will exhibit the same general saturation characteristic.

The slope of the capacitor curve labeled E_c is negative compared to the transformer saturation curve and is determined by the value of capacitance. The slope is shown positive in Figure 3.2A merely to simplify the analysis.

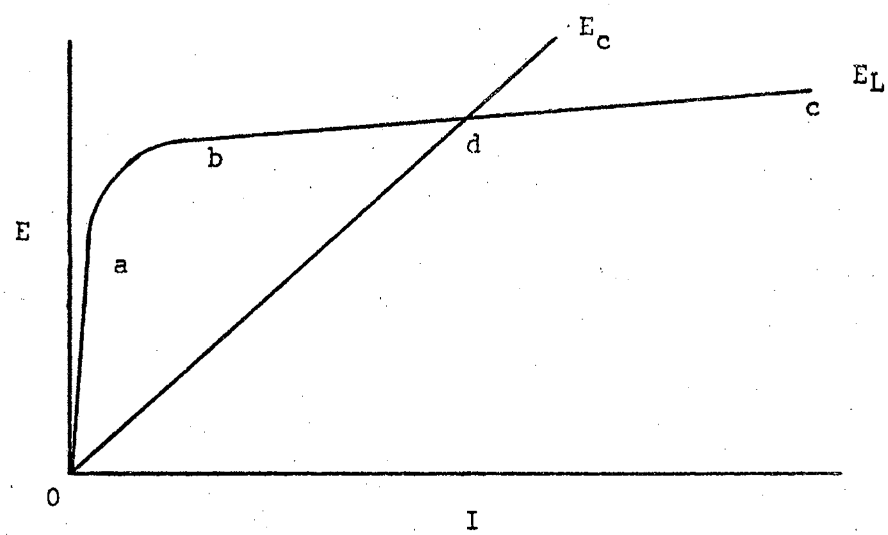
If a circuit like that shown in Figure 3.2A, but containing no resistance, is energized with some magnitude of driving voltage, there may be one or more ordinate points at which the circuit equation

$$E_a = E_L - E_c \tag{3.3}$$

is satisfied. If the applied voltage E_a is less than any ordinate in the region 0 a b d o bounded by the two curves, then one of the operating points satisfying the circuit equation will most probably be just below



A. An L-C Circuit with an A.C. Source



B. Volt-Ampere Characteristics of the Transformer and Capacitor of the Circuit in A.

Figure 3.2

the knee of the saturation curve, and a small magnitude of current I will flow. The circuit equation, however, will also be satisfied in the region beyond the intersection of the two curves. This operating point corresponds to very-high magnitudes of current. The region 0 a b d o can be called the inductive region, since the voltage across the inductance is greater than that across the capacitance. The region beyond the intersection can be called the capacitive region, since the voltage across the capacitance is greater than that across the inductance.

Since power circuits always display some resistance, the circuit equation to be truly representative must contain another term and takes the form

$$E_a = E_R + (E_L - E_c) \qquad (3.4)$$

A similar explanation to the one above can be given but is not as simple, since the three terms on the right side of Equation 3.4 do not all lie in the same plane as do the reactance values.

Jump Phenomena Prediction Technique

In an attempt to satisfactorily predict the points on a volt-ampere plot at which the ferroresonance jump phenomena will occur, a graphical construct was devised. The device not only made use of the transformer saturation curve and the capacitance characteristic but also utilized the resistance component as well. Its operation can be better explained with the use of Figure 3.3.

The data for the saturation curve in Figure 3.3 can be found in Table A1 of Appendix A and was obtained on an open-circuit test of a 3 kva, dry-type transformer. The several capacitor characteristics

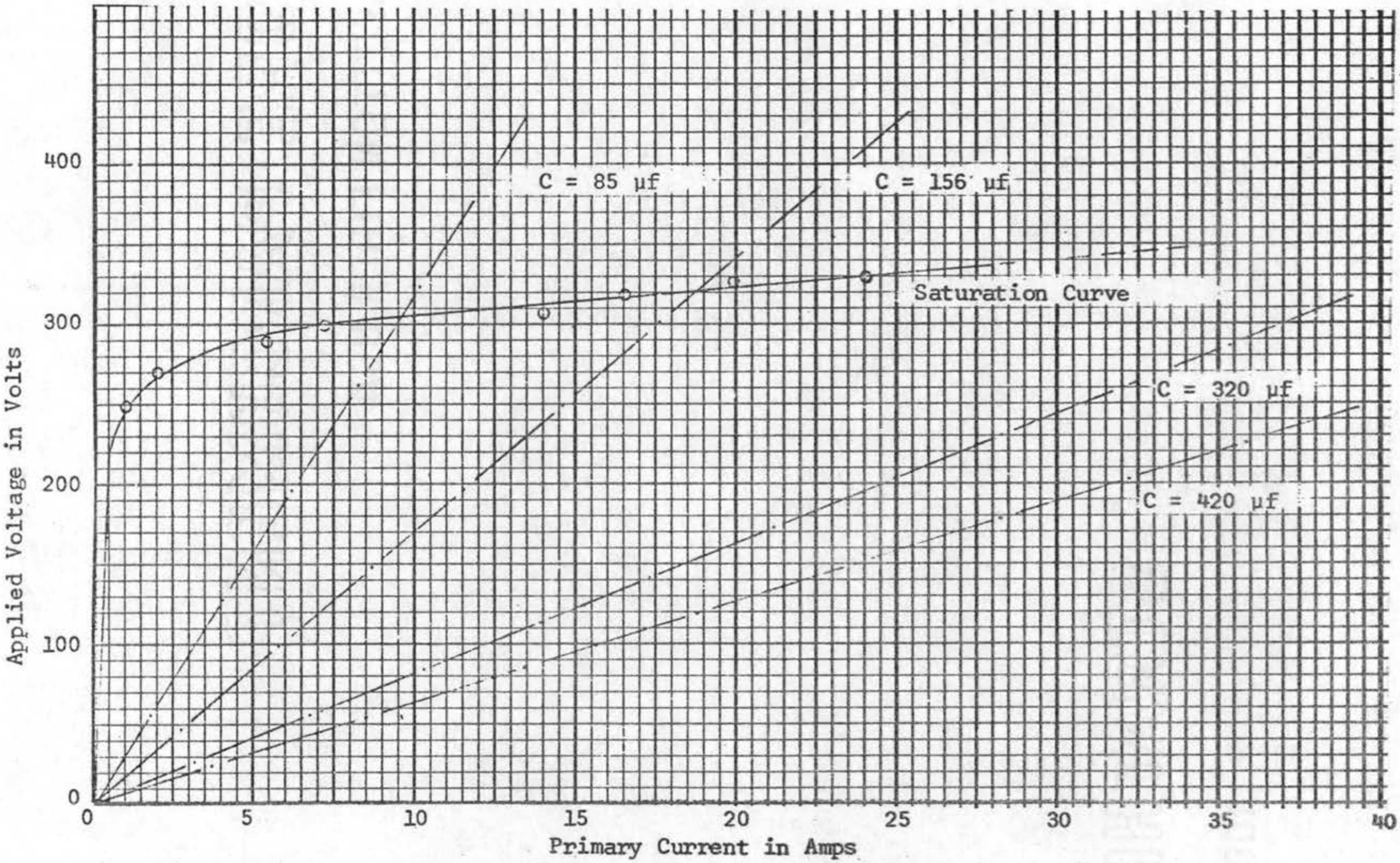


Figure 3.3. Volt-Ampere Characteristics for 3 kva Transformer and Capacitors

were obtained by a bridge measurement and the following sample calculation where a particular value of 85 μf was used.

$$\begin{aligned} x_c &= 1/\omega c \\ &= 10^6/(377)\,(85) \qquad (3.5) \\ &= 31.4 \text{ ohms} \end{aligned}$$

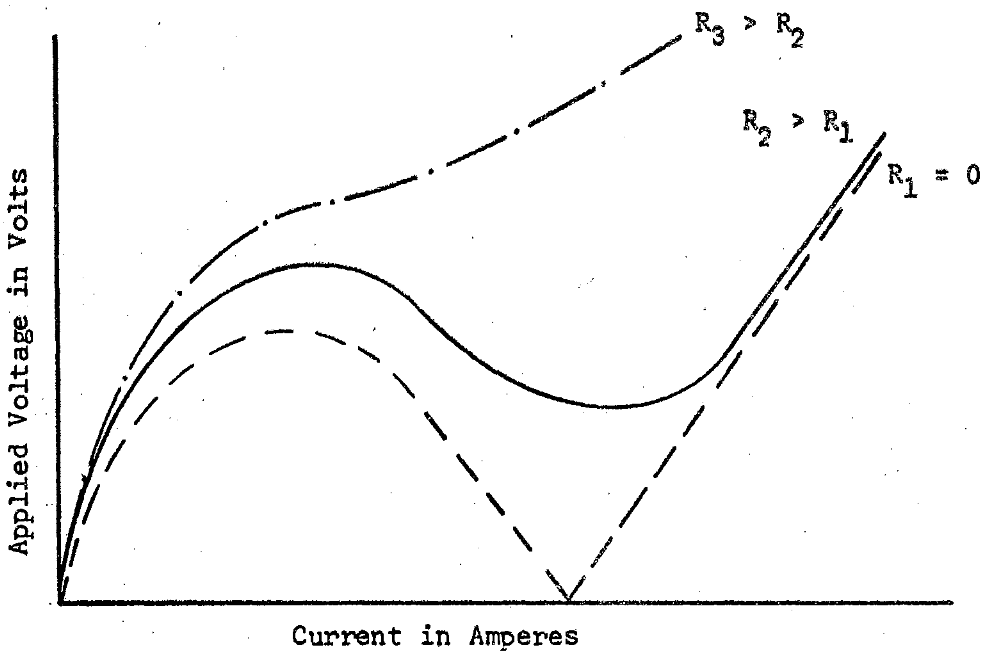
where $\omega = 2\pi f$

f = 60 cycles

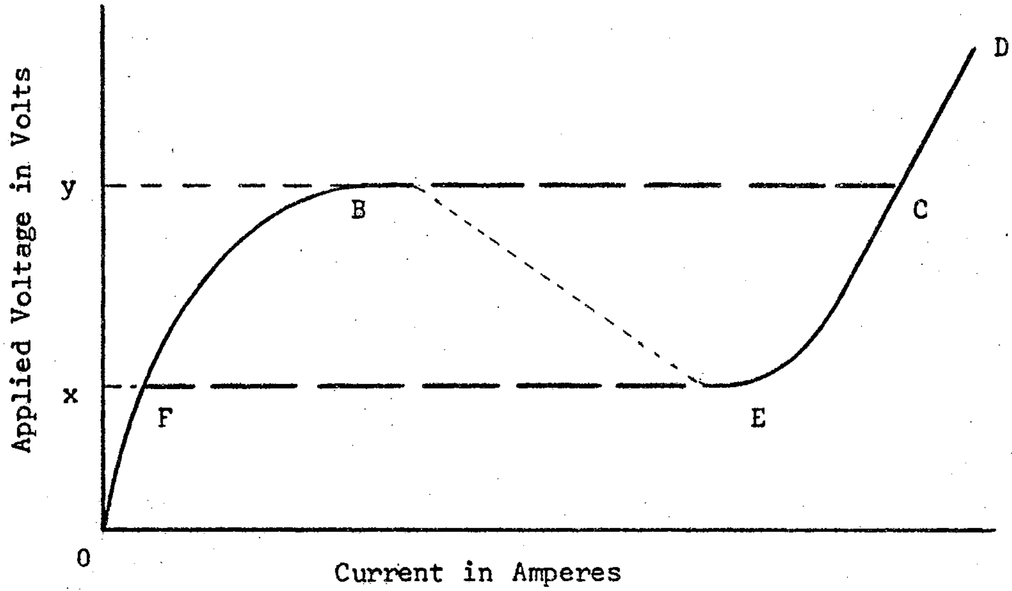
c = capacitance in μf (microfarads)

The ohmic value of the capacitive reactance gives the slope of the capacitance characteristic on a volt-ampere plot. The various capacitance characteristics are all linear and originate at the origin. The capacitor has no resistance and can be considered as purely reactive. The transformer, however, is a wire-wound device and, although highly inductive, must have some distributed resistance. The core losses and eddy current losses must also be reflected back as some type of resistance so that the transformer then exhibits an impedance consisting for the most part of inductive reactance and resistance. The distributed capacitance in the transformer is so small that it is not considered significant to the impedance.

Figure 3.4A shows the curve of the current through a series circuit as a function of applied voltage for several values of resistance. For a circuit containing no resistance, the curve will be double valued and will intersect the abscissa at some magnitude of current determined by the value of capacitance and inductance used in the circuit. As



A



B

Figure 3.4. Volt-Ampere Characteristics of a Series Ferroresonant Circuit

resistance is increased, the curve will not dip completely down to the abscissa but will tend to have a local minimum. As resistance is further increased, the voltage values corresponding to the local maximum and local minimum of the curve will approach each other and finally as still more resistance is added the double-valued characteristic will completely disappear, and the curve will be single valued and monotonically increasing.

Figure 3.4B is a volt-ampere characteristic of a series RLC circuit for a specific value of resistance. As the applied voltage to the circuit is increased from zero, the current increases along curve OB. At some voltage around point B, say Y, the circuit is not very stable, and a sudden increase in voltage will cause the current to change from a value corresponding to point B to a much larger value at point C. As the voltage is increased, the current will follow the curve CD and will increase as the voltage is increased. If the voltage is decreased from that at point C, the current will not jump back to the same value as that at point B but will decrease with the voltage. When the voltage is decreased down to point E, the circuit again becomes unstable; and a further decrease in voltage will cause the current to jump back to point F. A further decrease in applied voltage causes the current to decrease along the curve FO.

The limiting values of voltage are X and Y. Any value of voltage greater than Y will cause the circuit to go into a state of ferroresonance, and once in this state any value of voltage smaller than X will bring the circuit back into a normal operating state. Any change in circuit parameters such as resistance, inductance, or capacitance can produce the jump phenomena.

The volt-ampere characteristic of the circuit resistance is not shown in Figure 3.3, but the graphical construct takes the voltage across the resistor into account by displacing the capacitance characteristic from the reactance plane by a value normal to the plane whose magnitude corresponds to the voltage across the resistance. The magnitude of the applied voltage in equation form is

$$|E_a|^2 = |IR|^2 + |IX_L - IX_C|^2 \tag{3.6}$$

The graphical construct device utilized a straight wire whose angle in the reactance plane represented the slope of the capacitance. The wire was anchored at the origin and was displaced from the reactance plane by an angle determined by the voltage across the circuit resistance and capacitance at some magnitude of current.

Tests and Test Results

To test this particular method of predicting the points at which the current so abruptly changes in a series circuit, a stable operating point was established, and the applied voltage and current were recorded. The value of applied voltage was used at the recorded value of current to displace the capacitance curve in a plane normal to the reactance plane. The applied voltage corresponded to the distance between the saturation curve and the displaced capacitor curve at points common to the recorded current. Magnitudes of voltages were then scaled off between the displaced capacitor curve and the saturation curve and plotted against corresponding current values. Two such tests were conducted for different values of capacitance, and the predicted values are shown in Figure 3.5. A comparison of the predicted values and the

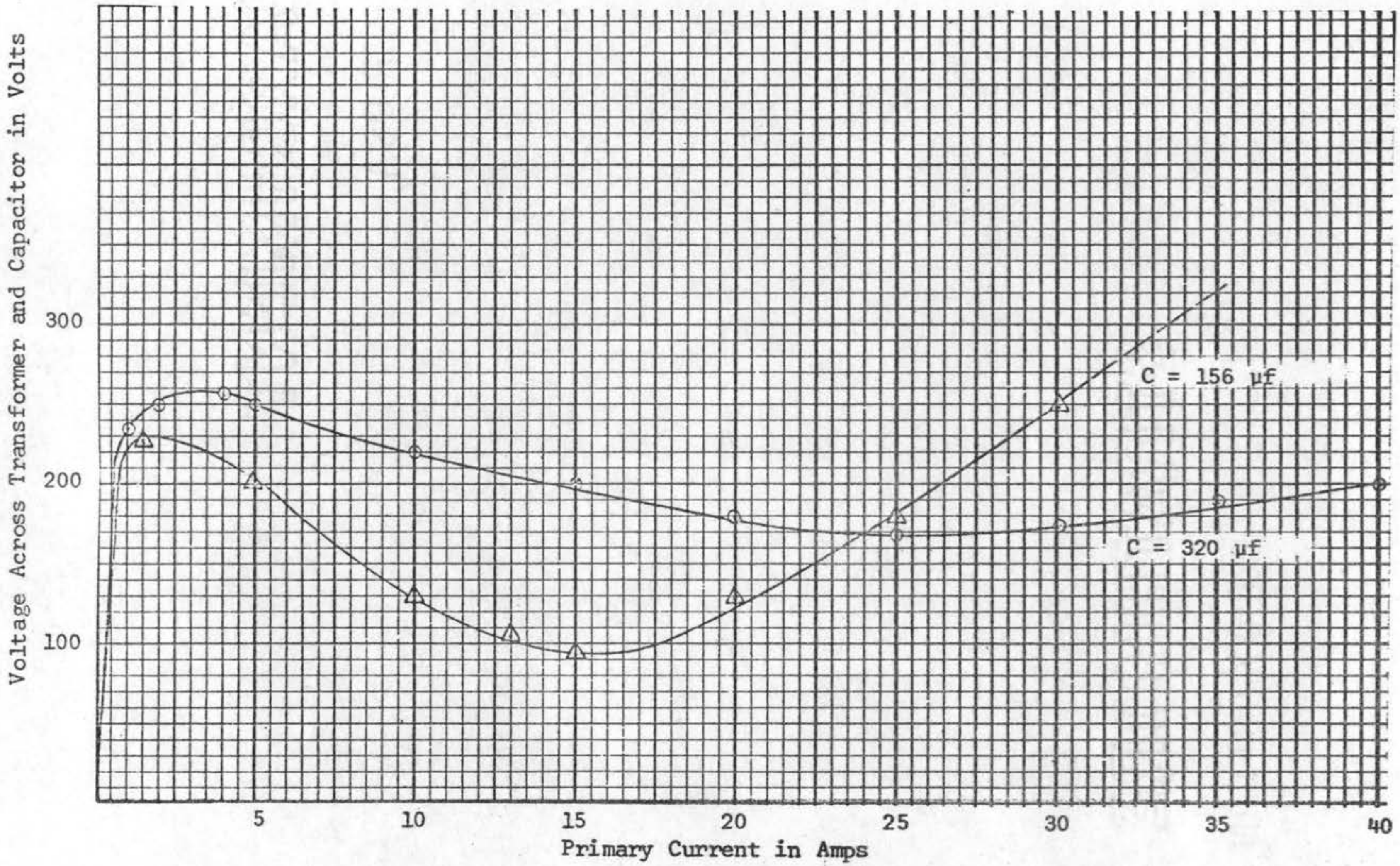


Figure 3.5. Volt-Ampere Curves for 3 kva Transformer in Ferroresonant State

test values of points B and E of Figure 3.4B are given in Table 3.1.

TABLE 3.1

PREDICTED AND TEST VALUES OF VOLTAGE AND CURRENT PRODUCING JUMP PHENOMENA IN A FERRORESONANT CIRCUIT

Capacitance	Predicted Value		Test Value	
	B	E	B	E
156 μf	225 volts	95 volts	220 volts	115 volts
	2 amps	16 amps	2 amps	19 amps
320 μf	260 volts	165 volts	240 volts	172 volts
	3 amps	35 amps	3 amps	23 amps

The difference between the predicted and test values for the circuit going into the ferroresonant state are quite small and are well within the tolerances of the measuring apparatus. The difference in predicted and test values at which the circuit came out of ferroresonance is larger, but the predicted values are still close enough to make this procedure of considerable value. It was observed through many tests that the current at which the circuit went into ferroresonance had a smaller rate of change per unit of voltage compared to that of the current when the circuit was coming out of the ferroresonant state. This can be observed in the curves of Figure 3.5.

Since no resistance was added to the circuit, but only the capacitance was changed, the curves in Figure 3.5 indicate what effect a change in capacitance has on a ferroresonant circuit. As capacitance is added to the circuit, the curves have a much less pronounced minimum and maximum. Both the maximum values shift to larger current values; and, as the capacitance is further increased, the maximum and minimum will completely disappear and the curve will cease to be double valued. At this and greater values of capacitance there will be no jump phenomena, and the transition into the higher-current region will be gradual as the voltage on the circuit is increased.

Figure 3.6 shows an oscillogram of current I, capacitor voltage V_C, and transformer-capacitor voltage $V_{T + C}$ as a function of time in a circuit undergoing a shift from the normal state to the ferroresonant state and back again to the normal state. This was accomplished by holding the circuit parameters constant and increasing the applied voltage slowly with a variac. The circuit consisted of a lumped capacitance of 320 μf, a lumped resistance of 3.8 ohms, and an unloaded 3 kva, dry-type 480/240 - 240/120-volt transformer. The instantaneous meter readings indicated the circuit went into ferroresonance at 240 volts and 5 amperes and came out of the ferroresonant state at approximately 175 volts and 25 amperes. The fourth trace from the top in the oscillogram is a reference voltage V_{ref} from an isolated circuit.

The current trace in the oscillogram indicates a very sudden increase in magnitude accompanied by a very large distortion in wave shape. The voltage across the capacitor also became quite large but has no visible distortion, while the distortion of the voltage across the transformer is clearly shown in the wave trace of the voltage across both transformer and capacitor $V_{T + C}$. No recording of the voltage across the transformer alone was made, but it had to be quite large also in order to provide the limited magnitude of $V_{T + C}$. Sometimes a higher than rated voltage across a transformer will cause insulation

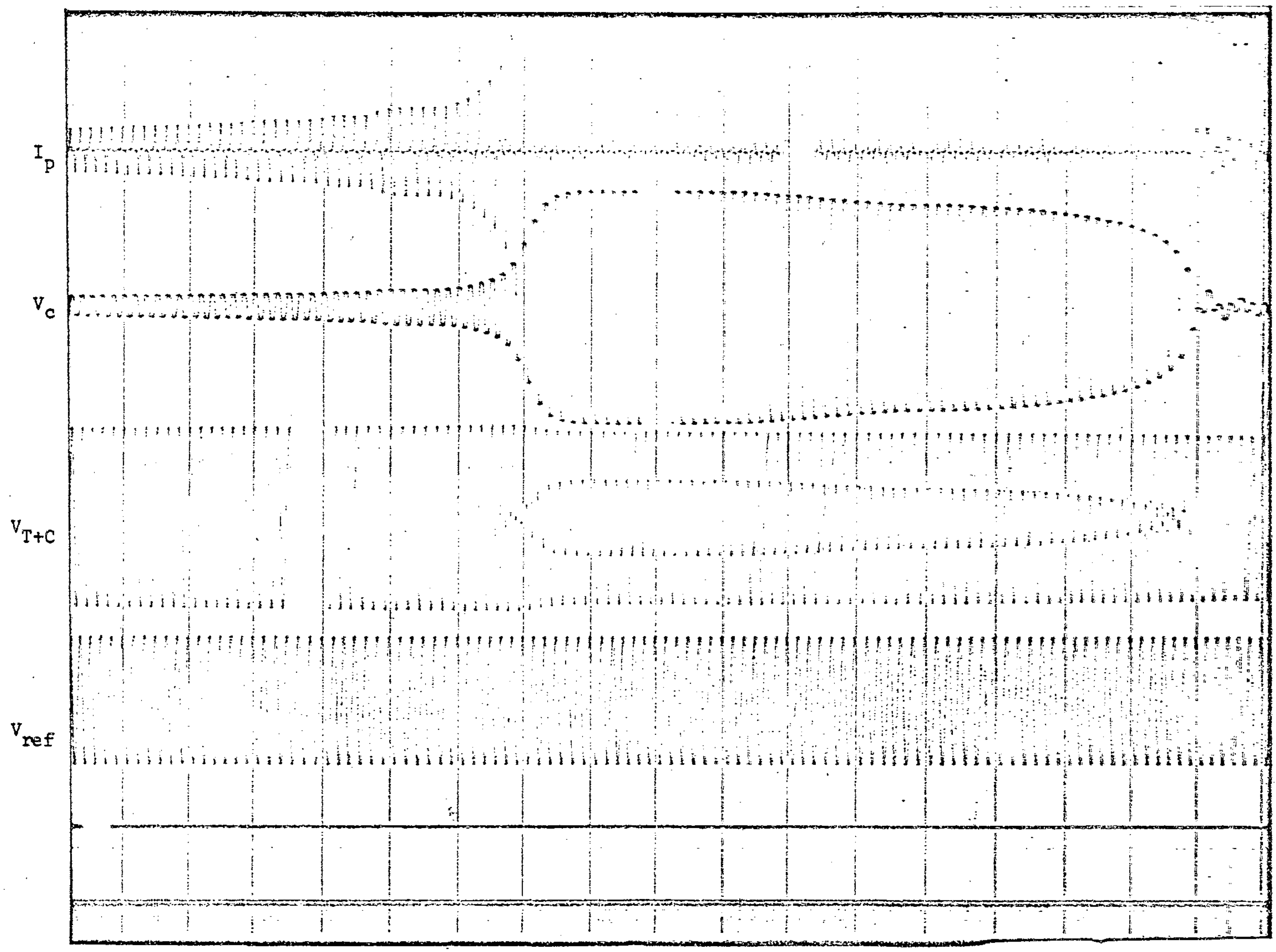


Figure 3.6. Circuit Undergoing Ferroresonant Jump Phenomena

breakdown.

The instability thus far described and discussed in this chapter is considered undesirable to the operation of power systems, and every effort is made to avoid this type of instability. This does not imply, however, that all such conditions are undesirable in other types of circuits. In a paper by C. M. Summers (21) several practical engineering applications of the ferroresonant phenomena were described, and some practical use has already been made of the type of bistable circuit described therein (22).

CHAPTER IV

SELF-EXCITATION

General Discussion

The term "self-excitation" used in this work should not be confused with the self-excitation of direct-current generators equipped for shunt-field excitation. According to the classical definition, self-excitation of alternating-current machinery describes the condition in which the excitation is provided by a capacitive current flowing in the motor stator windings. Self-excitation may occur in both synchronous and asynchronous machines regardless of the number of phases for which the machines are rated. A description of self-excitation in three-phase synchronous machines can be found in a paper written by J. W. Butler and C. Concordia (9).

Generally associated with the self-excitation of induction motors is the tendency of the motor to operate at some subsynchronous speed below the rated speed of the motor. Also associated with self-excitation is the generation of torques which cause the machine to vibrate and operate at a high noise level. An examination of the current will reveal that it is larger in magnitude than the normal operating current, and its waveform is quite distorted from the usual 60-cycle sinusoid.

Self-excitation of induction machines is related to ferroresonance in at least one way in that the same value of lumped capacitance can produce both conditions. It was found through testing that the starting of a motor on the secondary side of a transformer having a series capacitor connected in its neutral lead could shock the system into such a violent state of ferroresonance that the primary protective device operated to open the circuit before the motor reached half its rated speed. The term self-excitation is applicable only to the case where a rotating energy conversion device is included in the circuit and has no meaning otherwise.

For the purposes of this investigation, the term self-excitation will be used to refer to a state of motor operation where there is capacitance in the primary circuit supplying the motor and the motor has the capability of operating at speeds ranging almost from locked rotor to synchronous speed.

In recent years there has been a very large increase in the application of single-phase induction motors in the 3 to 7 1/2 horsepower range. This increase was brought about primarily by the increasing demand for central air conditioning for residential and small commercial applications. These types of load had been served by three-phase machines. Since the cost of providing three-phase service is (in some locations) quite expensive and the efficiency and reliability of large, single-phase motors has been improved, they have been employed in greater numbers to drive air-conditioning compressor loads.

The nature of these single-phase loads, on the other hand, has brought about other problems in some locations. In most cases the motor is directly coupled to the load and has to start fully loaded. The high torque required by the compressor load causes the motor to draw a large starting current from the source, and the accelerating time is larger than that of some other types of loads. In the case of such a load placed near the end of a long distribution feeder or on a small, high-impedance transformer or on a long service cable, the drop in voltage brought on by the large and long surge of starting current causes lights to dim and television images to shrink and sometimes roll.

Several types of corrections can be made to reduce or completely eliminate the described problem. The use of series capacitors is the most economical but has not been exploited. This is due to two reasons, one of which has already been discussed, and the other is the instability of self-excitation. Since nothing can be found in the literature on self-excitation of single-phase induction motors and the problem is recognized but not well understood, it is felt by the writer that the subject bears some experimental investigation. The problem is quite complex and a rigorous mathematical investigation will not at this time be considered, although some graphical constructs will be utilized.

The method used by J. W. Butler and C. Concordia (9) to set the limits of stability of three-phase motors employed the two-reaction theory of electric machinery. Since the two-reaction theory utilizes the transformation of the phase variables into direct and quadrature variables, new variables are introduced which sometimes create confusion to those who are not familiar with the method. Butler and Concordia, however, did establish limits of stability and showed the affect of applying series and shunt resistance to limit or completely eliminate self-excitation in three-phase motors.

Later, C. F. Wagner (23) made use of the induction motor equivalent circuit concept to also set limits of self-excitation behavior in three-phase machines. Much later a paper was presented by V. G. Bauman,

O. V. Ivanov, and B. I. Konarov (24) which made use of the linearized circuit of C. F. Wagner and presented information on three-phase machines similar to that of Wagner.

A single-phase motor is quite different from a three-phase motor. One of the outstanding differences is the way in which the single-phase motor must derive its starting torque. There are many different ways that starting torque may be achieved in single-phase motors, but two of the highest starting torque motors use the repulsion-start, induction-run and capacitor-start, induction-run principles. Both types of motors are used on high-starting torque loads but utilize different methods to provide the starting torque. The capacitor-start motor has a large capacitor in its auxiliary winding which produces the phase shift necessary for a large starting torque. The auxiliary winding is mechanically switched out of the circuit as the machine comes up to speed. The repulsion-start motor has a commutated winding to help produce a high-starting torque. A centrifugally-operated device short circuits all the commutator segments when the motor reaches about 75 per cent of synchronous speed.

Test Facilities and Procedures

Two separate test facilities were used to obtain the charts, photographs, and data presented in this chapter. The first test facility was an actual field test which involved a 5 horsepower, 240-volt, repulsion-start, induction-run motor supplied through a 7,200-240/120-volt single-phase distribution transformer. A diagram of the test circuit is shown in Figure 4.1. Three 2,400-volt capacitor units were placed in the ground connection of a 7,200-240/120-volt single-phase

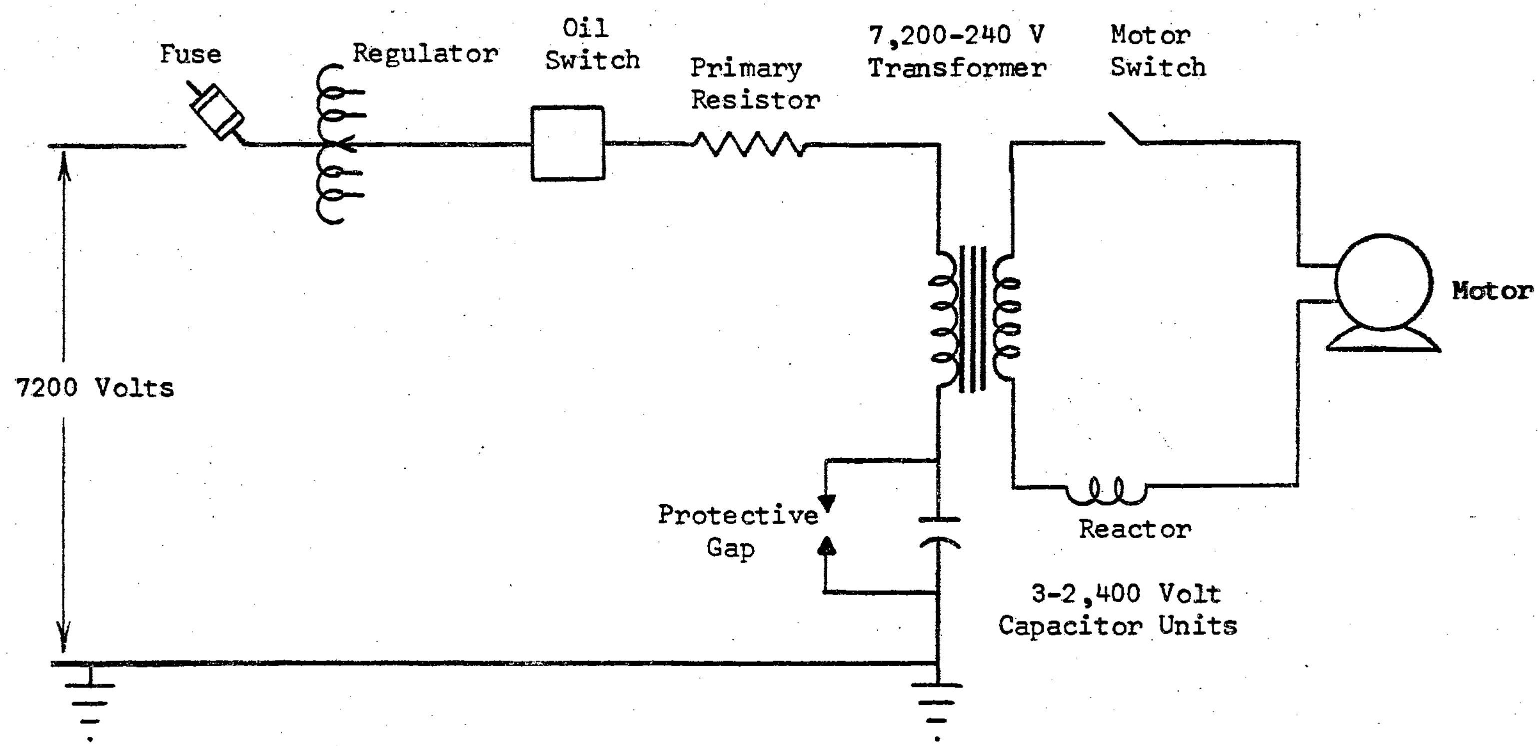


Figure 4.1. Field Test Circuit Diagram

transformer to provide approximately 5 per cent compensation. It was found that ferroresonance occurred nearly every time the primary circuit was energized, because the capacitors were not provided with a shunting device or protective gap. Since self-excitation was the objective and not ferroresonance, the circuit was energized with the capacitors shunted by a grounding cable. After the circuit was excited, the capacitor shunt was removed, and ferroresonance would not reoccur.

The motor was started numerous times and under varying load conditions. A prony brake was used as the loading device. At different times a 10-, 15-, and 25-kva transformer was used to supply the motor. A step-voltage regulator was used in the primary to change the voltage applied to the circuit. The primary resistance was changed by using a tapped, wire-wound resistor. The secondary impedance was varied through the use of a reactor and finally by a large coil of insulated wire.

It was found that changing the components of the primary and secondary circuits of such a high-voltage system was quite difficult and time consuming. Out of many attempts to attain self-excitation, only once was it observed and then only for a few moments. During this short period of self-excitation, the motor accelerated up to about 600 r.p.m., remained at that speed for a few moments, and then accelerated on up to its rated speed of about 1,750 r.p.m. At the 600 r.p.m. speed the motor appeared to vibrate and was noisy. The rms value of current read during this brief period was 87 amperes with a motor voltage of 172 volts. Rated load current for the motor was 32 amperes at 220 volts.

Due to the extreme difficulties experienced in the field of varying the circuit parameters, it was decided to try to obtain self-excitation on a smaller scale which could be accomplished in a test laboratory. A capacitor bank was constructed from salvaged 240-volt capacitors which formerly served as ballasts in street lights. Each of the 46-capacitor units in the bank was provided with a switch so that the capacitance could be varied in steps of about 12 μf. A three-phase 0- to 135-volt variac was reconnected to obtain a single-phase 0- to 270-volt range to supply the 3 kva, 480/240-240/120-volt, dry-type transformer. The variac was fused and supplied from a 220-volt, single-phase circuit of a three-phase, 2,400-220-volt transformer bank. The transformer bank was supplied from a 2,400-volt feeder of an isolated 12-megawatt generating system.

A load bank having a continuous variable resistance from 2.5 to 30 ohms was used in the primary to change the circuit resistance. A 3/4-horsepower, motor-generator dynamometer set was employed as the motor and loading device. The generator was a d-c separately excited machine directly coupled to the motor. Two types of 3/4-horsepower motors were used during the tests. A repulsion-start, induction-run motor was used for the earlier tests, and a capacitor-start, induction-run motor was used for the later tests. The centrifugal switches operated at about 1,000 r.p.m. for both machines. The rated speed for the capacitor-start motor was 1,725 r.p.m., and the rated speed for the repulsion-start motor was 1,750 r.p.m. The motors were connected for 220-volt operation, and the transformer was connected 1:1. A diagram of the laboratory test circuit is shown in Figure 4.3. A picture of the test apparatus appears in Figure 4.2.

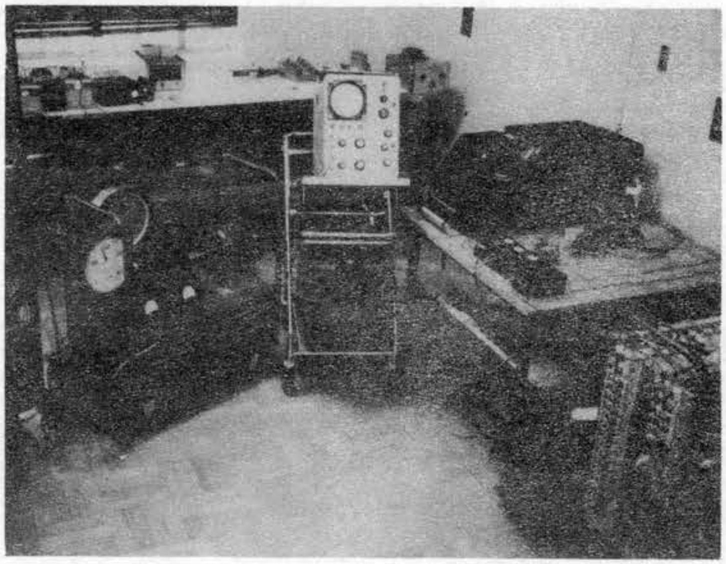


Figure 4.2 Arrangement of Laboratory Test Equipment

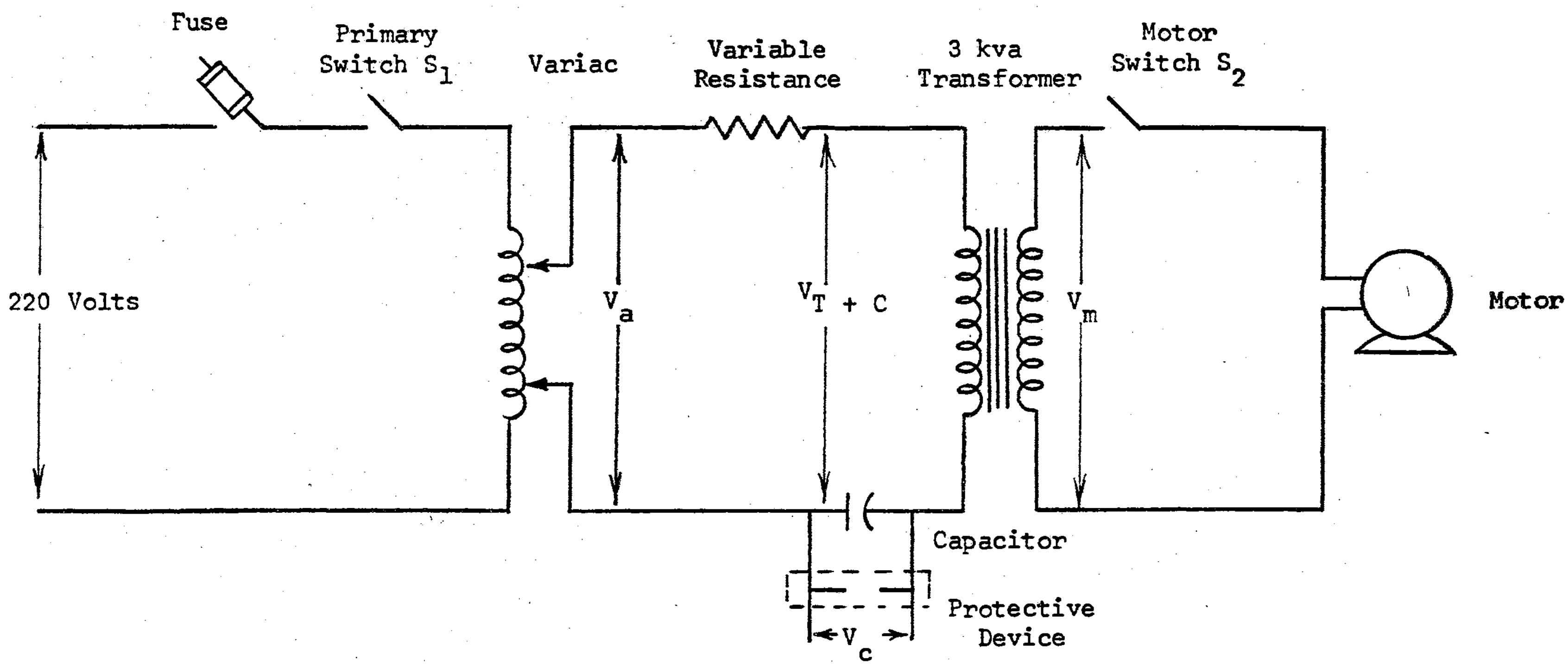


Figure 4.3. Laboratory Test Circuit

Oscillographic Recordings

Figure 4.4 is an oscillographic recording of the circuit currents and motor r.p.m. of a repulsion-start motor operating at approximately 1,200 r.p.m. The primary circuit contained a lumped external resistance of 4.7 ohms and a lumped capacitance of 320 µf. The motor was directly coupled to the generator which was unloaded at the time the recording was made. The motor was switched into the circuit after the primary had been excited, came up to 1,200 r.p.m. quickly, and began vibrating and creating an extremely loud noise. The top trace in the record is the primary current, and the middle trace is the motor current. The bottom trace is that of an a-c tachometer directly connected to the generator shaft. The oscillograph recording speed was 28.5 inches per second. The applied voltage was set at 185 volts and remained at that value throughout the test. To make sure the motor was not operating under just a low-voltage condition, the capacitors were temporarily shorted. The motor then accelerated on up to near 1,800 r.p.m. and ran very quietly until the short was removed. The motor then quickly decelerated to 1,200 r.p.m. and again began to vibrate excessively. Several polaroid pictures of the two currents described above were made from an oscilloscope image. One of these was enlarged to obtain data necessary to perform a Fourier series analysis on the wave shape (see Appendix B). Both the oscilloscope picture and the oscillograph recording show the current wave shape to be repeating every five cycles of a normal 60-cycle sinusoid.

A series of tests were run on the repulsion-start and capacitor-start motors, and it was observed that if the motors were gradually

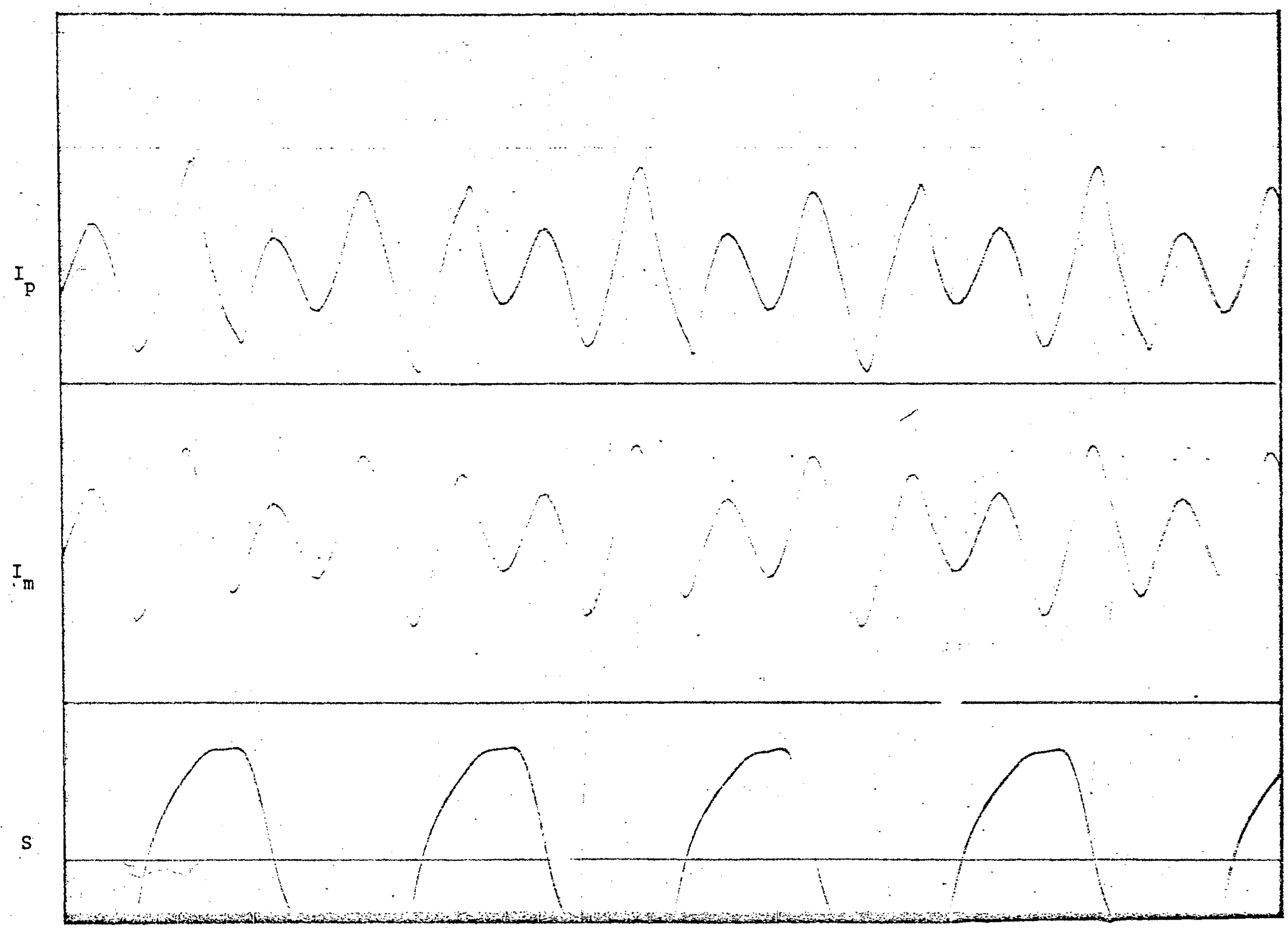


Figure 4.4. Repulsion-Start Motor in State of Self-Excitation

loaded while in a state of self-excitation, they would slow down with load until the mechanism providing the starting torque operated. The motors would then operate at that speed or oscillate in and out of that speed regardless of the degree of additional loading. To determine the effect of loading on a motor in the self-excited state, an external switch was placed in the start-winding lead of the capacitor-start motor. Several interesting observations were made by using the external start-winding switch.

It was found that the start winding had a great deal to do with the speed at which the motor operated for a particular set of circuit conditions. With the primary circuit already energized, the motor was started and accelerated up to about 1,000 r.p.m. which was the speed at which the centrifugal switch normally disconnected the start winding from the motor circuit. It was observed that the motor would continue to operate at 1,000 r.p.m. and in a state of self-excitation until the start winding was opened manually. On opening the start winding manually the motor would quickly accelerate on up to almost 1,800 r.p.m. accompanied by large motor currents and extremely bad vibration. Manually switching the start winding back into the circuit would have no effect, since the centrifugal switch had also operated to open the start-winding circuit. The motor, which was running light, in this condition would draw about five to ten times its rated current (depending on the applied voltage) and would operate at this condition until the motor winding overload protective device operated to open the motor circuit.

The second very interesting observation came when the motor was gradually loaded when operating in the condition just described with the start winding manually opened to prevent the start winding from being reconnected into the motor circuit. With the motor running light at rated speed, the oscillograph recording showed the primary and motor currents and the motor voltage to be in a state of "modulation." That is, there appeared to be a low-frequency envelope which contained a specific number of 60-cycle oscillations inscribed within each cycle of the envelope. As the load on the motor was increased, the motor decreased in speed; and the oscillograph recording indicated that the number of 60-cycle oscillations contained in each period of the envelope began to decrease in number. After the motor was loaded to stall condition, the oscillograph recording showed that the number of "modulated" cycles decreased from twenty-eight at the beginning of the record to twenty-seven, then twenty-six, and continued to decrease in number until no modulation was observed at the stall condition. A section of the oscillograph recording is shown in Figure 4.5.

The circuit parameters at which the data in Figure 4.5 was taken were a source voltage of 220 volts, a lumped series capacitance of 320 μf, and 3.7 ohms of lumped primary resistance. These parameters were all held constant during the load test. The test was repeated a number of times with the same results. The output of a d-c tachometer connected to the generator shaft is displayed as the bottom trace of Figure 4.6 which is a section of a chart recorded under the same loading conditions as those of Figure 4.5. The applied voltage in this test was 210 volts with 320 μf of capacitance and 3.7 ohms of resistance in the primary circuit. The top trace is the motor current, and the second from the top trace is the voltage across the capacitor. The third from the top trace is the voltage appearing across both the transformer primary and

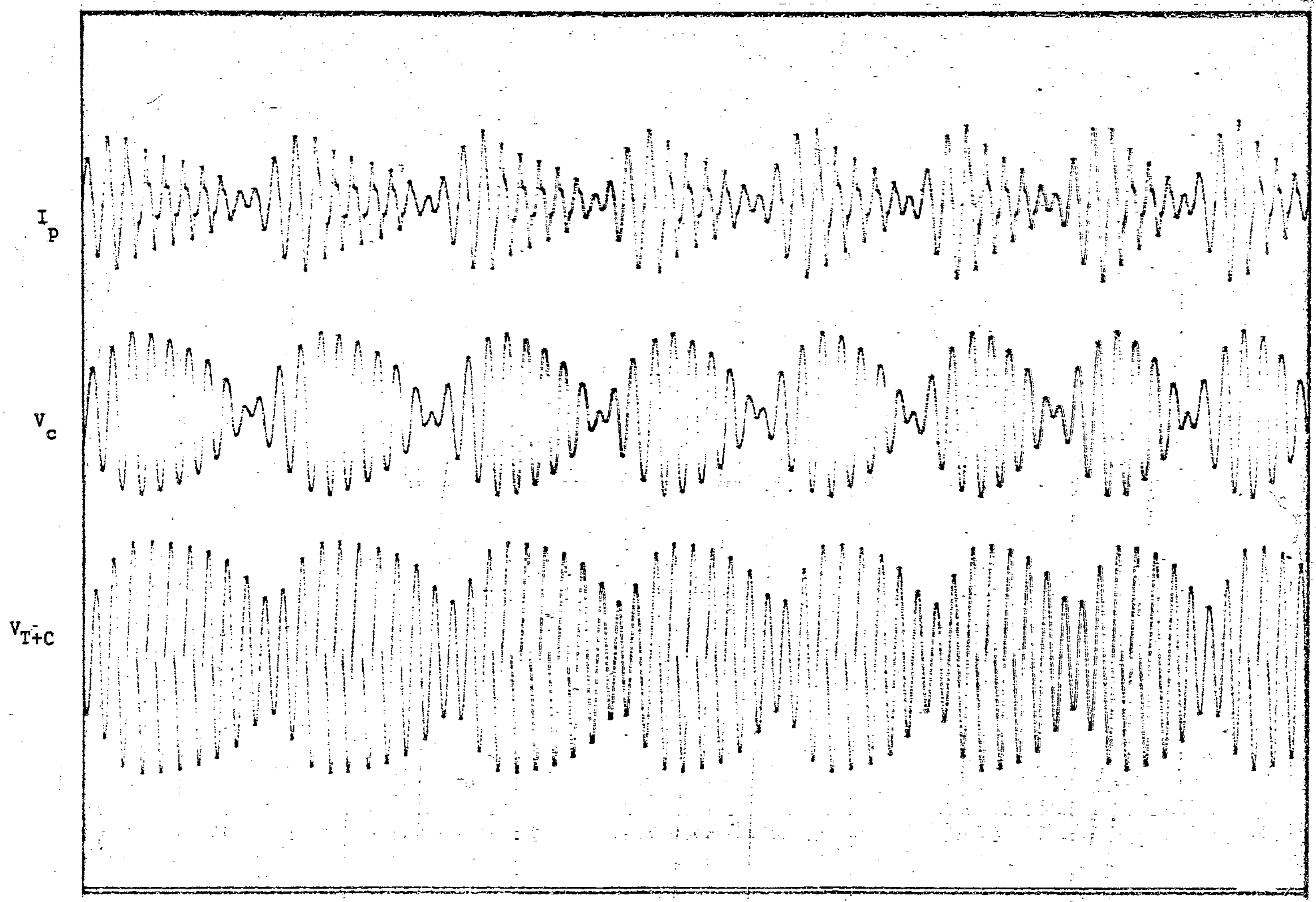


Figure 4.5. Capacitor-Start Motor in State of Self-Excitation as Load is Increased

capacitor connected in series. The tachometer output indicated that the speed of the machine was oscillating synchronously with the current and voltage envelopes. The rate of increase at which the envelope expanded was greater than that at which it contracted. The acceleration of the motor was likewise greater than the deceleration, and the oscillation between these two states caused the frequency and magnitude of vibration to be high.

The procedure for obtaining the traces in both Figure 4.5 and 4.6 was the same. The primary circuit was energized with the capacitors shorted to prevent ferroresonance. The capacitor short was then removed, and the oscillograph started. The secondary switch S_2 was then closed, and the motor accelerated up to rated speed. The motor was gradually loaded down to stall speed through the load on the generator. Chart speed for these tests was 3.5 inches per second.

Figure 4.7 shows a motor developing a state of self-excitation as it accelerates from standstill. The circuit conditions were the same as those in Figure 4.5 except the capacitance was changed to 156 μf, and the source voltage was raised from zero on up to rated voltage after the motor switch had been closed. A close inspection of the chart will show that as the source voltage was raised, the motor accelerated on up to about start-winding switch operation speed. The centrifugal switch did not operate, and the motor speed remained at about 1,000 r.p.m. as the voltage continued to increase. Figure 4.8 shows another section of the same chart where the start winding was opened manually. The motor speed oscillated for a few moments and then the motor accelerated on up to rated speed. At one point on the chart the motor was operating for a few moments above synchronous speed. As the motor reached rated

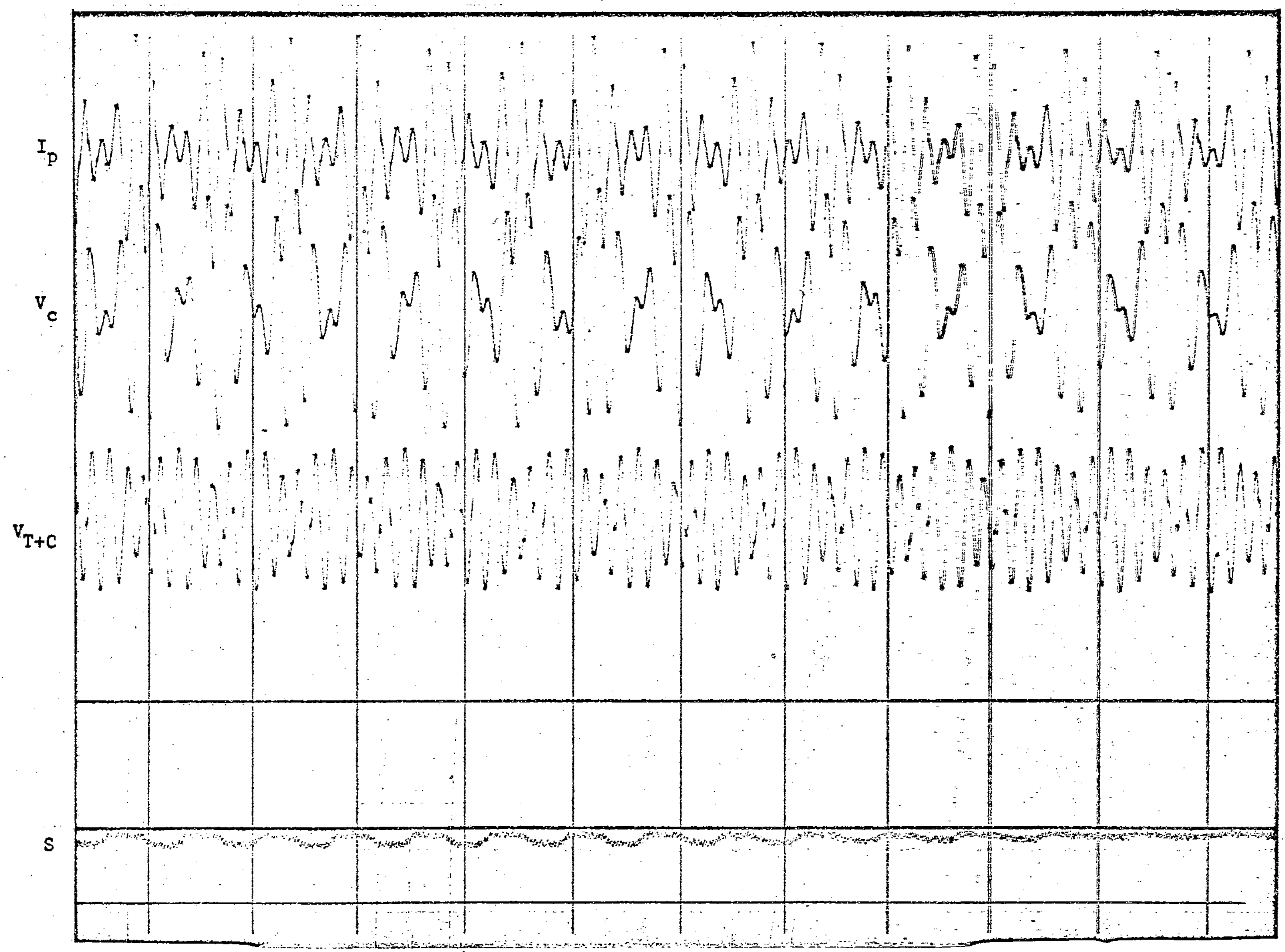


Figure 4.6. Self-Excitation of Capacitor-Start Motor with 210 Volts Applied

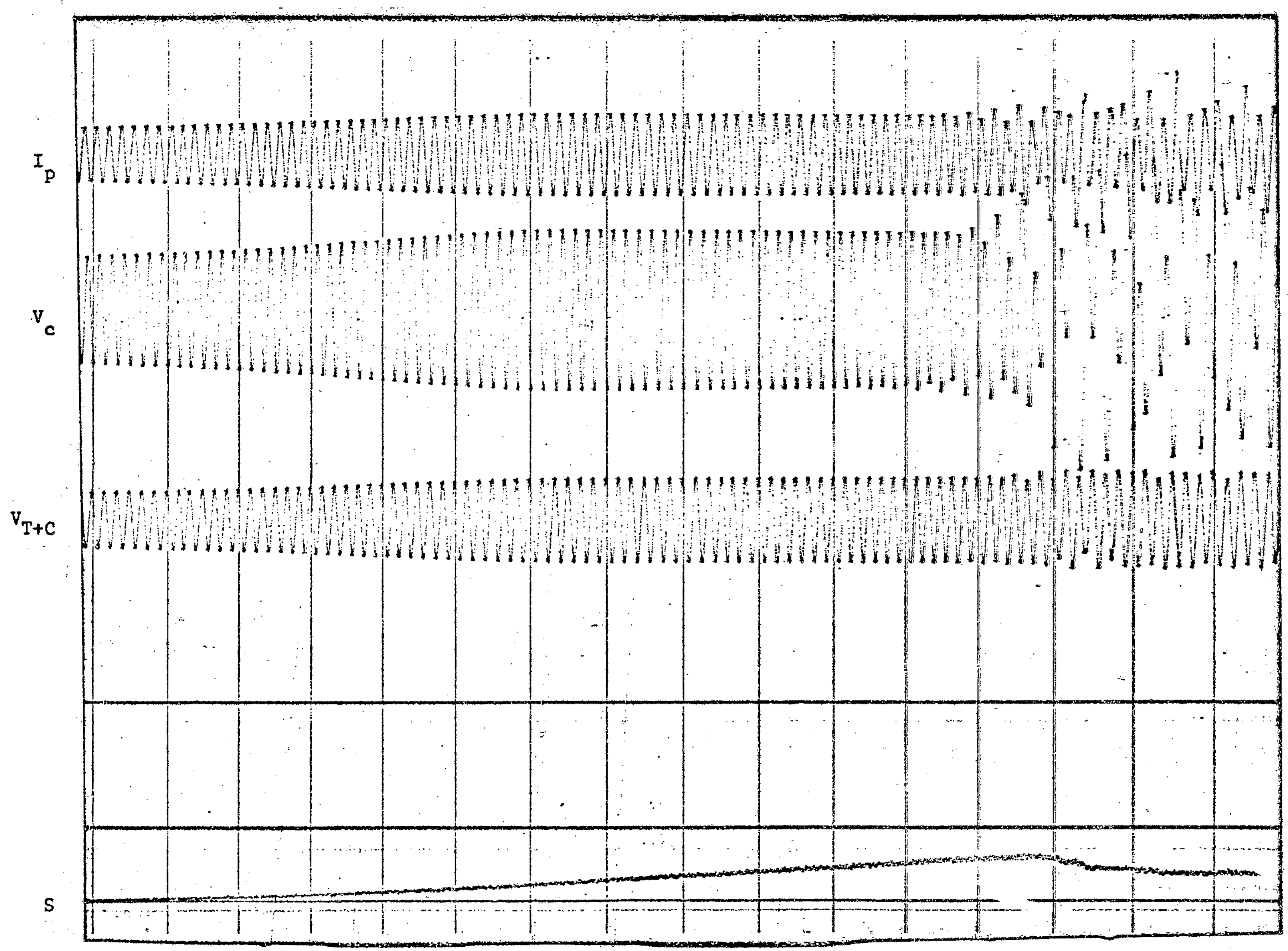


Figure 4.7. Motor Developing a State of Self-Excitation

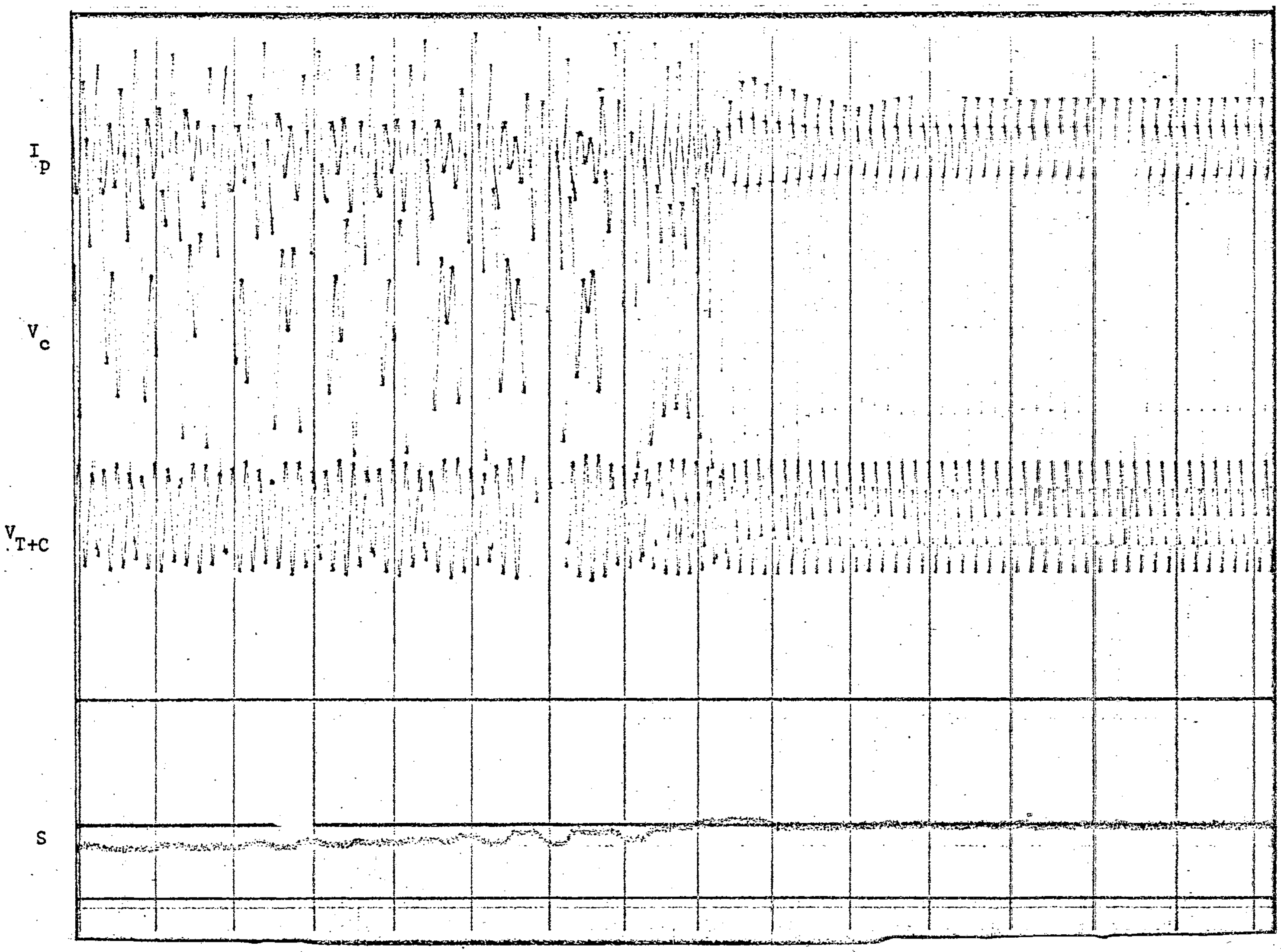


Figure 4.8. Motor Behavior as Start Winding is Opened Manually

speed, the motor current increased to a very large value accompanied by a correspondingly large increase in capacitor voltage. The voltage across both the transformer and capacitor, as can be seen from the third trace from the top in the recording, remained approximately the same in magnitude but became more distorted.

Figure 4.9 shows traces of the motor current, capacitor voltage, and motor voltage for a repulsion-start motor as the applied voltage was raised gradually from its rated value of 220 volts up to about 240 volts. The primary circuit contained 320 μf of capacitance and 3.7 ohms of lumped resistance. The motor was running light. As can be seen from the charts, the motor current modulation envelope changed as the voltage was raised. The motor, which was running very roughly, smoothed out in speed as 240 volts was reached and drew excessive current. The modulating envelope disappeared completely, and the motor current and voltage were distorted by what appeared to be a very large third harmonic.

A series of tests were run for various values of applied voltage in which the capacitor motor was allowed to accelerate up to rated speed, the start winding opened, and the motor gradually loaded down to stall condition. These tests showed that the modulating envelope became more discernable and contained more 60-cycle oscillations as the applied voltage was increased. As the motor was loaded in each case, however, the modulating envelope contained fewer and fewer 60-cycle oscillations so that the beginning of the 210-volt chart looked like the later section of the 220-volt chart, and the beginning of the 200-volt chart looked like a still later section of the 220-volt chart and so on to 180 volts, which was the lowest value of applied voltage

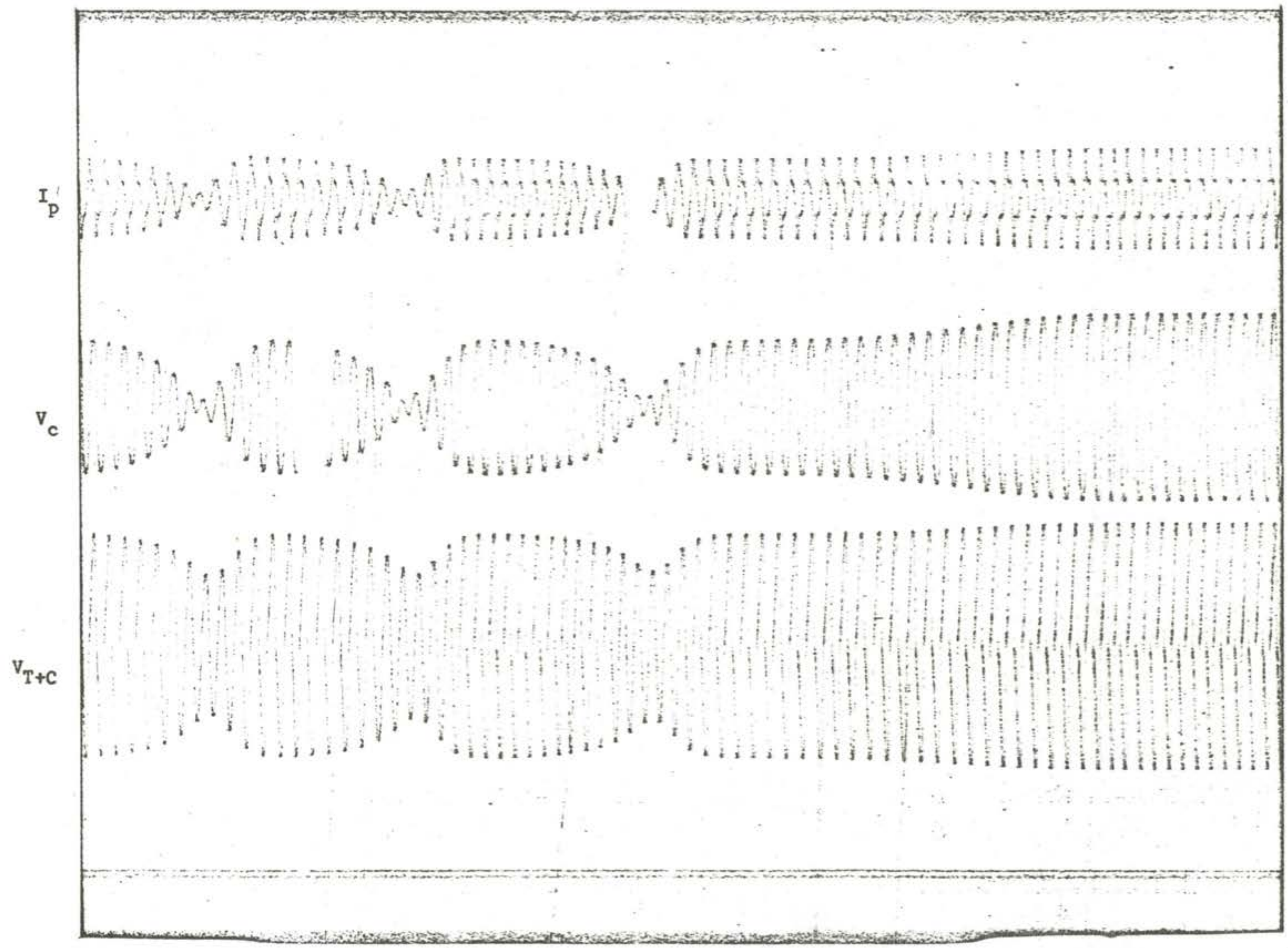


Figure 4.9. Motor Response as Voltage is Gradually Increased from Rated Value

used in this particular series of tests. There was a small difference in the amplitudes of the wave shapes for the corresponding sections of the various charts.

Figures 4.10, 4.11, and 4.12 are sections of a chart showing the motor current, capacitor voltage, and the transformer-capacitor voltage for a motor operating light as the applied voltage was slowly raised. The length of the complete chart taken for the test was about 12 feet, and its length prohibits its use as a whole. A brief description of the chart along with sections appearing in Figures 4.10, 4.11, and 4.12, however, may enable the information on the chart to be presented. The first section of the chart, shown in Figure 4.10, was taken at a low voltage and shows all traces to have a low amplitude but so uneven that no modulating envelope can be observed. As the voltage is raised, the traces begin to look like those shown in Figure 4.11 where wave shapes of several frequencies are observed. As the voltage is increased further, the modulating envelope appears; and the number of 60-cycle oscillations contained within each period of the envelope begins to increase. The final section, Figure 4.12, shows no modulation but an extremely high value of current and capacitor voltage.

It appears from the results of the tests (1) where the load was varied with a fixed voltage and (2) where the voltage applied was changed and load varied, that the number of 60-cycle oscillations contained in the modulating envelope could be controlled by either the applied voltage or the load.

Theory of Operation and Graphical Analysis

To try and explain graphically what might be taking place during

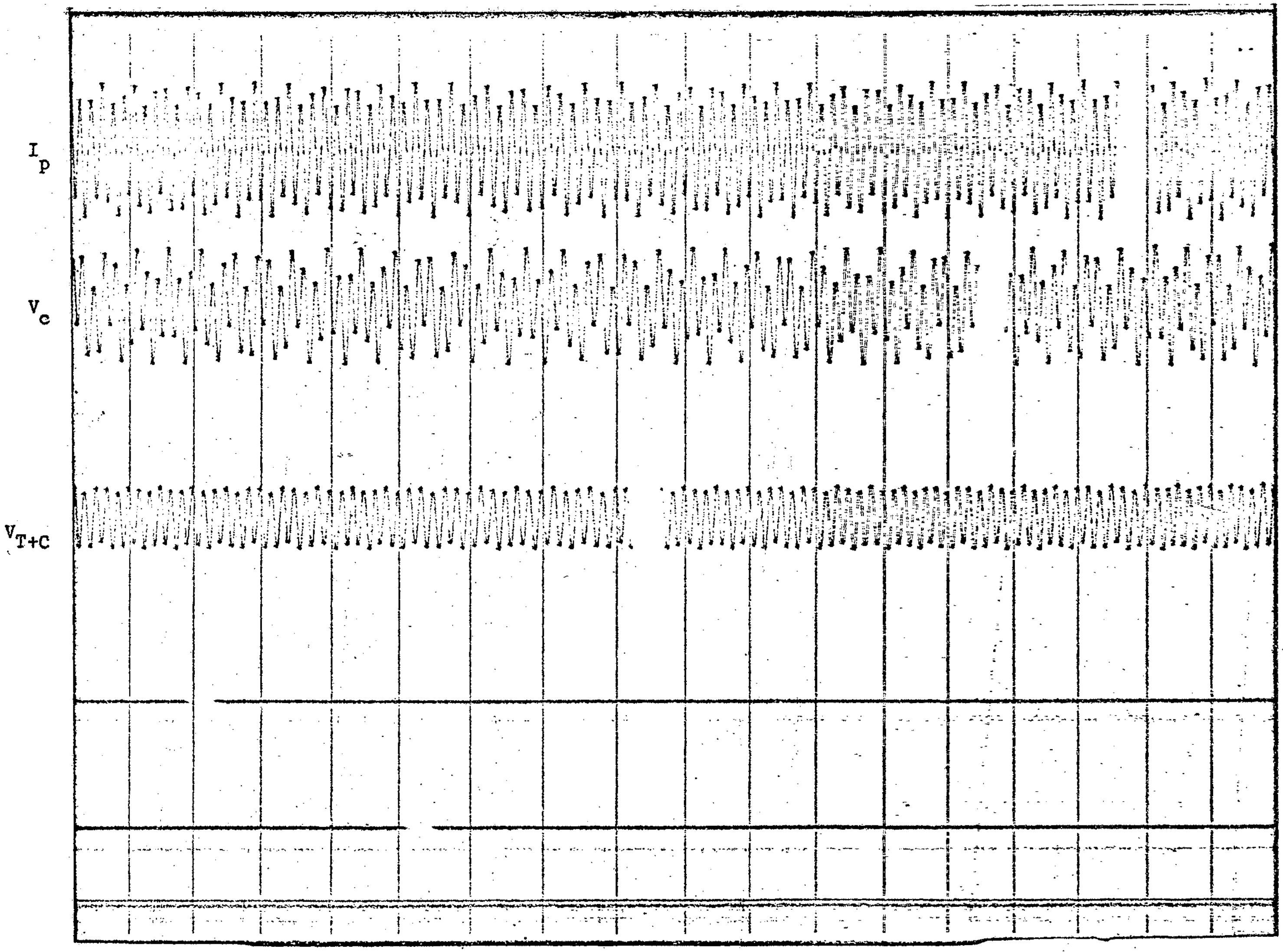


Figure 4.10. Motor Behavior at Low Value of Applied Voltage

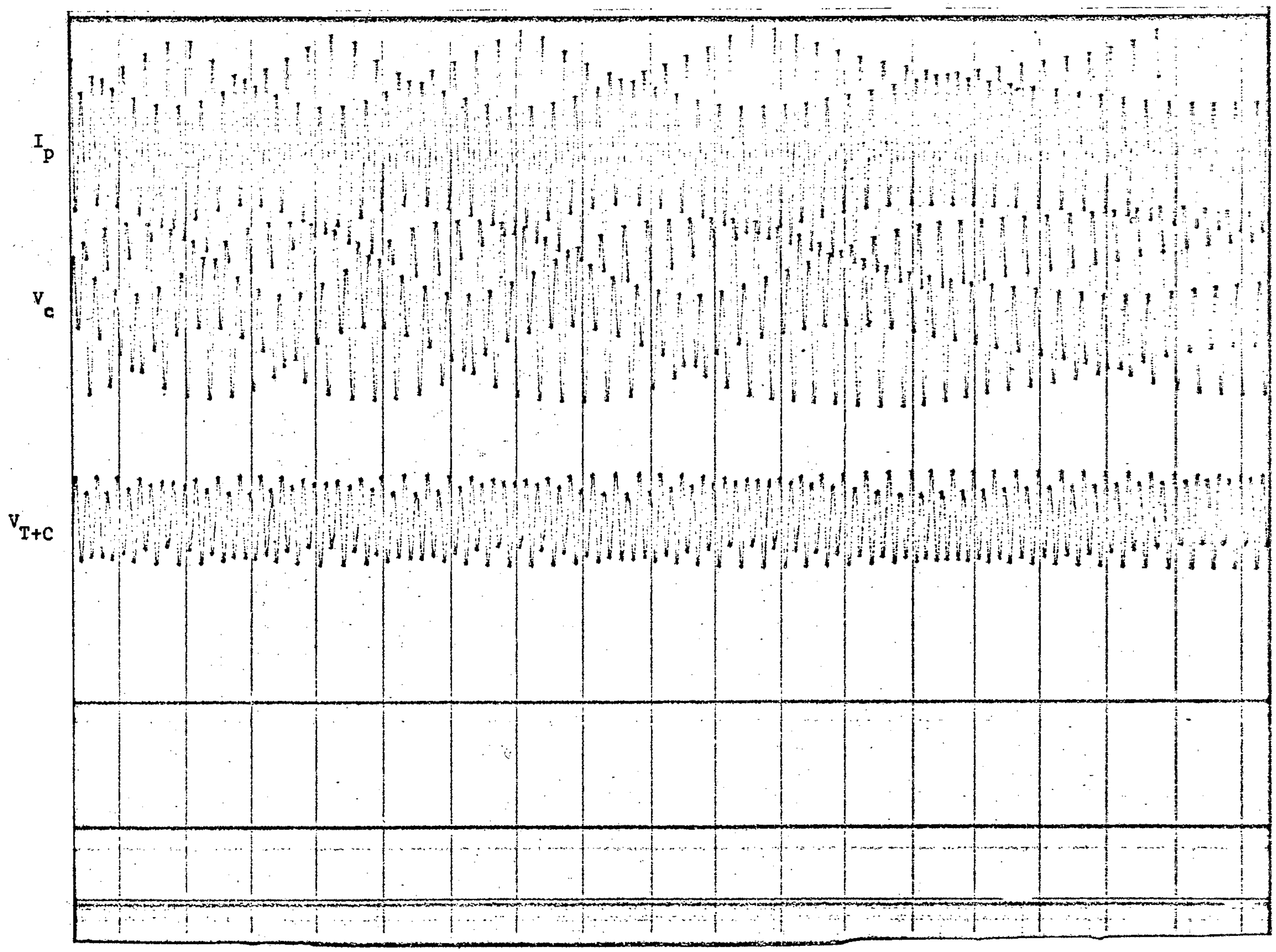


Figure 4.11. Variations in Current and Voltage as Applied Voltage is Increased

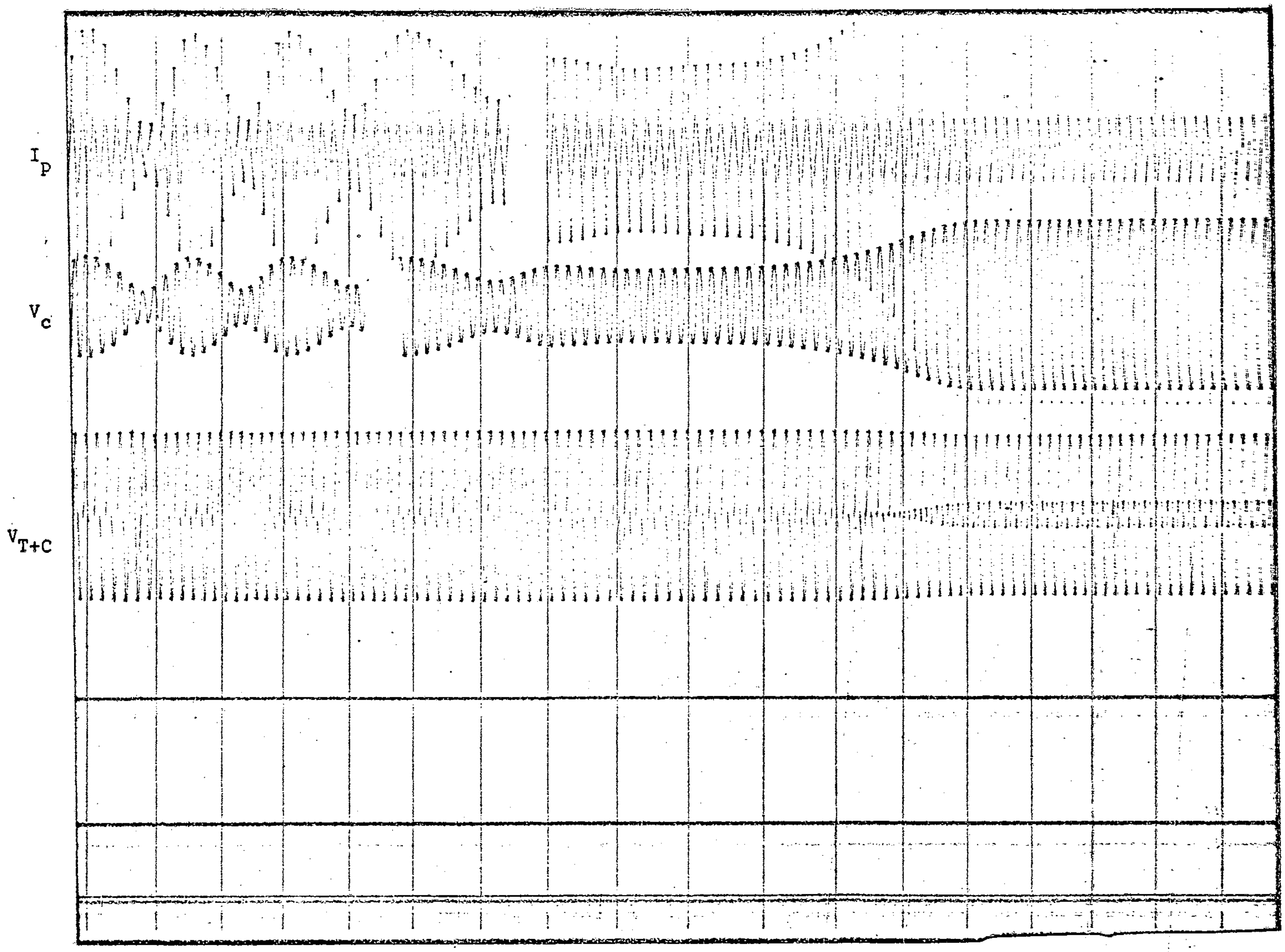


Figure 4.12. Motor Operation Advancing to the High Saturation State

the voltage and load down series of tests, a composite volt-ampere curve of the transformer and motor for rated r.p.m. and for a locked-rotor condition was obtained from test data. The data appears in Tables A2 and A3 in Appendix A, and the curves appear in Figure 4.13.

The knee of the composite motor-transformer, volt-ampere curve is not nearly as pronounced as that of the transformer curve alone. The saturated portion of the curve, however, is almost identical to that of the transformer curve as can be seen by a comparison with the transformer curve in Figure 3.3. In Figure 4.13 the locked-rotor curve, curve B, is practically linear over the range of voltages applied during the test. As the motor speed decreases from rated speed (with other parameters constant), curve A will approach curve B. For some speed between rated and locked rotor, the volt-ampere curve will be located somewhere between curve A and curve B, depending on the speed of the machine. Also in Figure 4.13 are plotted the curves for several values of capacitance. Since the capacitance is linear over the range of currents and voltage applied, their characteristics are straight lines. No less than 56 μf of capacitance was used in the tests on self-excitation, because the motor would not start for values less than 56 μf.

If the same graphical construct is employed as was in Chapter III on ferroresonance, a similar volt-ampere characteristic can be produced which will predict when the motor will operate entirely in the well-saturated region of the curves shown in Figure 4.13.

The volt-ampere relations shown in Figure 4.14 were obtained graphically the same way as those in Figure 3.5. The predicted and test values of currents and voltages at which the circuit changes

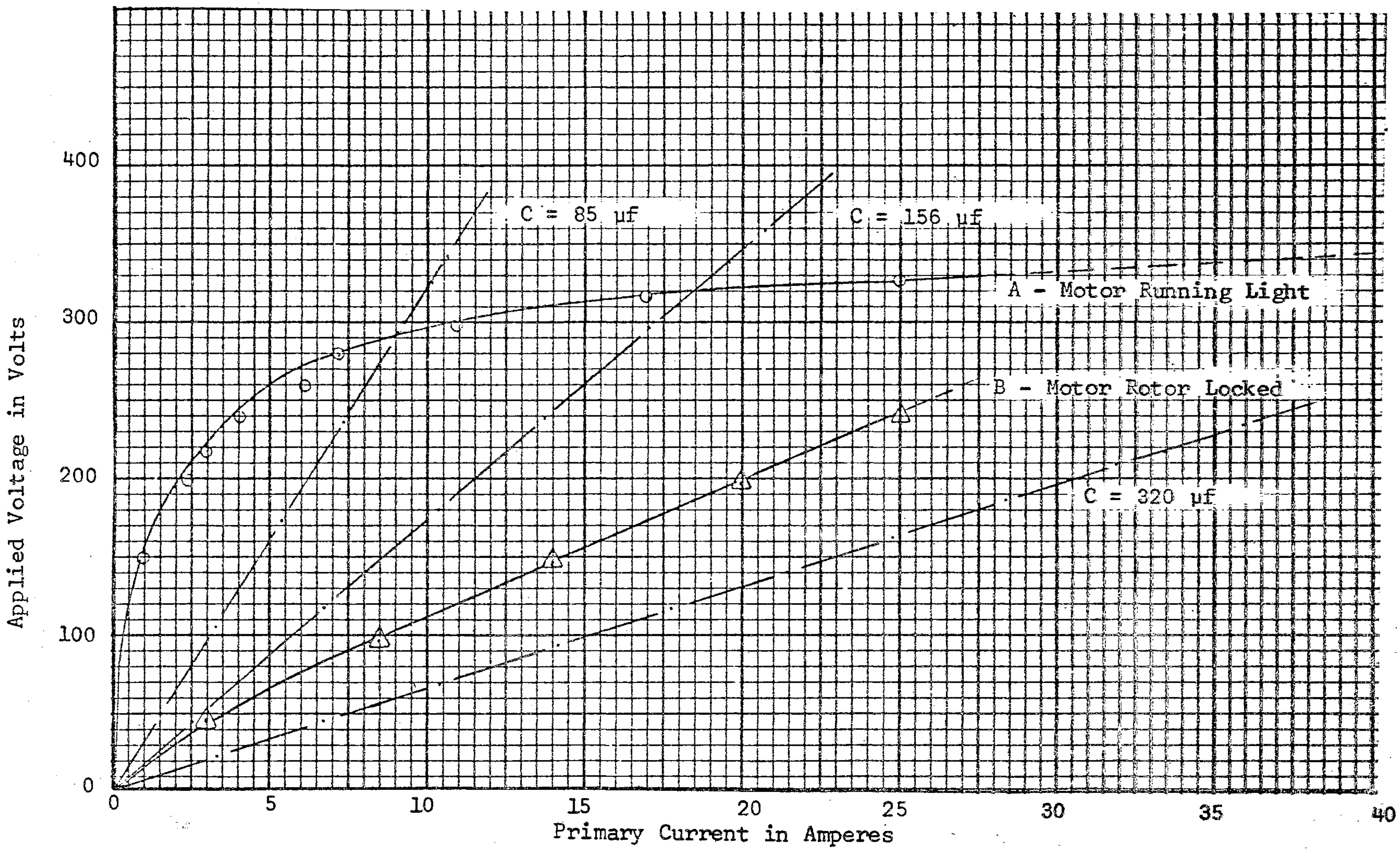


Figure 4.13. Volt-Ampere Characteristics of Transformer-Motor Combination and Capacitance Curves

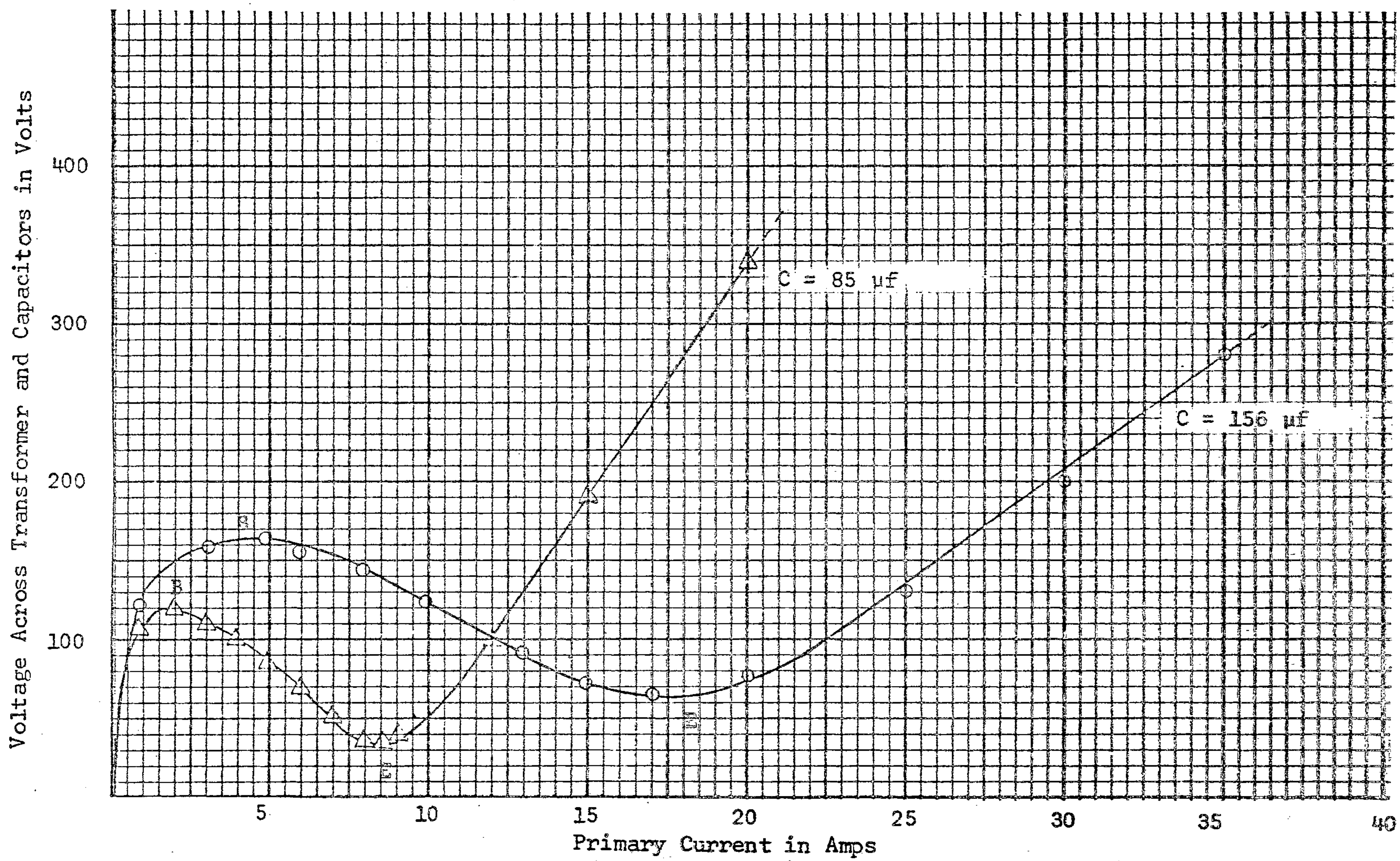


Figure 4.14. Volt-Ampere Curves for Capacitor Start Motor in Self-Excited State

state of operation (points B and E of Figure 4.14) are given in Table 4.1.

TABLE 4.1

PREDICTED AND TEST VALUES OF VOLTAGES AND CURRENTS AT WHICH A SELF-EXCITED MOTOR CIRCUIT CHANGES STATES OF OPERATION

Value of Capacitance	Predicted Value		Test Value	
	B	E	B	E
85 µf	120 volts	35 volts	135 volts	58 volts
	2 amps	8.5 amps	6.7 amps	9.5 amps
156 µf	160 volts	80 volts	145 volts	102 volts
	4 amps	17 amps	13 amps	18 amps

There are some differences between the predicted and test values. These differences may be the result of the variation in the transformer-motor composite volt-ampere curve due to a speed variation. All predicted values were made with the curve at rated speed. It was observed, however, that just before the circuit changed to the high-current state, the motor was not operating at rated speed. For the curve with 85 µf in the primary, the speed was about 1,400 r.p.m. before the jump in current. It was also noted that for voltages less than the voltage at which the circuit jumped into the high-current condition, the motor current and voltage and capacitor voltage were being modulated as has already been described. They were oscillating from a very-low to a very-high value and in some cases were doing so at such a slow rate that the instantaneous reading meter pointer swings could be detected on the ammeter and voltmeter. Some oscillations were so large that their limiting values could actually be read from the meter scales.

The oscillographic recording shown in Figure 4.15 verifies this condition for a circuit containing 320 μf of capacitance and 3.7 ohms of resistance in the primary. To obtain the trace, the source voltage was varied above and below a mean of 220 volts. The voltage across the transformer-capacitor combination varied about 20 volts above and below 170 volts. The current oscillations were observed to fluctuate between 10 and 25 amperes as read on the instantaneous meter as the circuit moved into and out of the high-current state. The motor was running light during the test.

The third trace of Figure 4.15 is the voltage across the transformer-capacitor combination and indicates by the darker section in the middle of the trace that the transformer was being saturated to such a high degree that the voltage wave shape was heavily distorted. The capacitor-voltage trace, which is the second trace, shows no saturation or distortion which was to be expected.

It can be concluded then that when a capacitor is placed in the neutral lead of a single-phase transformer serving a motor load, the motor may develop several states of operation. The first state could be called the normal state and would be recognized by the motor operating quietly at rated speed and drawing normal load current.

The second state may also occur at rated speed, but a closer look would find the motor current to be very large in magnitude and distorted in wave shape. The motor would be quite noisy and would be vibrating badly. The third operating state would find the motor operating at some speed below rated speed and at the same time drawing a large

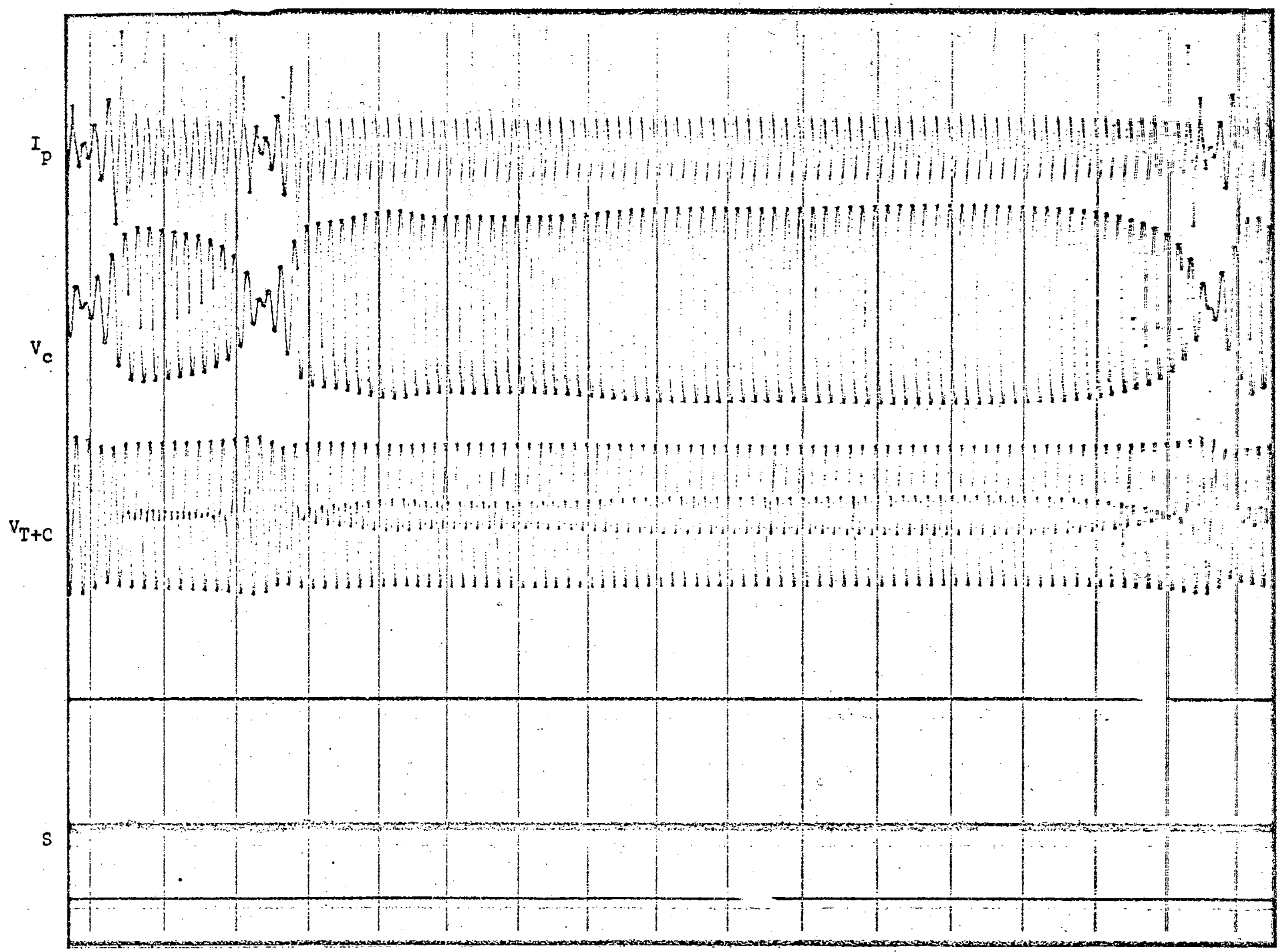


Figure 4.15. Jump Phenomena of Motor in Self-Excited State

distorted current.

The fourth state is an oscillatory state. That is, the current would oscillate between a small value and one very large. These oscillations would be grouped such that the magnitude of each succeeding cycle of 60-cycle current would increase until a maximum was reached and then the magnitudes would decrease to a minimum. The number of 60-cycle oscillations in a period between two succeeding minimums may vary from a large number down to a wave shape like that of the third state. The speed of the motor in the fourth state would be oscillating in unison with the current.

The difference in the number of 60-cycle oscillations contained in the modulating envelope of the current in the fourth state of operation might occur in the following manner. It was observed that for a constant load, an increase in voltage caused the oscillations to increase in number. With reference to Figure 4.13, if the voltage across the transformer and capacitor is increased in magnitude, this new value can no longer satisfy the circuit requirements at that value of current; and the current would have to increase. Stating this in another way, the longer ordinate representing the new value of voltage could not satisfy the distance between the capacitor curve and the machine-transformer saturation curve at the old value of current, so the ordinate would have to shift to the right. Since the circuit equation can be satisfied at two points on the curves in Figure 4.13, the ordinate in the high-current or capacitive section would also have to move to the right for an increase in voltage. It might have to move farther to the right in the capacitive section than in the inductive section because of the slopes of the curves in each section.

The current would, therefore, have a wider range to cover, and the time taken for the period of oscillation would be longer.

It was also found that due to loading, the number of cycles contained within each oscillatory period decreased. If the voltage remains constant and the transformer-motor saturation curve is shifted down and at the same time the capacitor curve increases its slope from the reactance plane, then the high-current and low-current voltage magnitudes move toward each other; and the period of oscillation between the two values decrease. The saturation curve moves down because the motor approaches the locked-rotor characteristic, and the capacitor curve changes its slope with the reactance plane due to loading of the machine. It may well be the action of the external resistance in the primary circuit which causes the oscillations between the two limiting magnitudes of current. This aspect should be pursued further and checked out through some sort of electromechanical simulation of the circuit.

It has been shown that single-phase motors will operate in one of several states beside the normal, desired state and that the start winding has some effect as to just which state the motor may finally operate in. So undesirable are these abnormal states of operation that great effort has been made to provide corrective measures which will cause the operation of the circuit to return to normal.

CHAPTER V

CORRECTIVE MEASURES

General Discussion

Shunt-connected capacitors seldom experience voltages higher than their voltage rating and, therefore, require little or no protection. Series-connected capacitors on the other hand do require some type of bypass or protective device to shunt them in the event of large current surges. A series capacitor is generally subject to four current conditions. These are (1) normal-load current, (2) high current due to short circuits, (3) large currents due to ferroresonance, and (4) the high currents associated with motor starting and self-excitation. No corrective measures should be required for the normal flow of load current if the capacitor is sized correctly before it is installed. The other three conditions are not normal operating conditions and may be recognized as transient currents which would cause the circuit breaker or fuse to operate if they were sustained.

As discussed in Chapter II, the voltage developed across a series capacitor is proportional to the IX_c drop and should not exceed 115 per cent of the voltage rating of the capacitor. Since the short-circuit current of a circuit is limited only by the impedance of the circuit from the fault to the source, the current at times can attain very-large values. The reactance of the series capacitor is fixed, and, therefore, the voltage across the capacitor is a function only of the line current. Because the capacitive reactance of capacitors reduces the circuit impedance, the short-circuit capability of the circuit is increased. Some tests have revealed that series-connected capacitors experience over ten times rated voltage during fault conditions (6).

To eliminate capacitor failure and interruption of service, most series-capacitor installations should be protected from overvoltage by some appropriate bypass device, or the capacitor should be rated to handle the high abnormal voltage. Present-day technology requires the cost of capacitors to increase as the square of the voltage, so power system economics generally point to some sort of protective device. Protective devices generally take the form of resistors, spark gaps, shorting contacts, and voltage-sensitive materials such as thyrite. Some very elaborate bypass schemes have been reported (5, 25-27). Due to the severity of the first few cycles of fault current and the comparative slowness of circuit breakers, they cannot be employed to protect such an installation.

Resistors can be applied in two ways in the circuit containing the capacitor. They may be connected in shunt across the capacitor or in series with the capacitor. Regardless of the connection, resistors increase the power loss in the system and are highly undesirable on power systems for that reason. Resistors act as damping agents on oscillatory systems and may be used on systems where power loss is sacrificed for system stability.

Some studies have been made to determine the effect of applying resistors to systems subject to ferroresonance and self-excitation (9, 16, 18, 23). The amount of resistance and how it is to be used depends on the other circuit parameters, but enough can be added to completely eliminate the abnormal condition. The writer observed this during some of the tests involving ferroresonance and self-excitation. Because of the losses connected with the use of resistance for correcting these abnormal conditions, other types of corrective measures have been studied.

Probably the most common type of corrective measure for series-capacitor overvoltage due to a fault current is the spark gap. It may be used alone or coordinated to operate as part of an over-all protection scheme. When used alone, the gap has the disadvantage of not being dependable at low voltages and producing oscillation peaks of high amplitude as well as burning of the gap terminals. The burning of the gap decreases the effectiveness. Some of the newer schemes incorporate several gaps, choke coils, contactors, and possibly a transformer into a protective device. The cost of such a device is large and prohibits its use except on large installations. In some protective control circuits, thyrite has been used to limit the over-voltage problem. In still another the simple spark gap is used with permanent magnets to bias the gap. The function of the magnets is to elongate the arc, thereby quenching it in a shorter period of time.

Development of a Semiconductor Device

It occurred to the writer during the laboratory and field tests on ferroresonance and self-excitation that there might yet be another way of reducing overvoltages caused by these abnormalities without reducing the effectiveness of the capacitors. To return a circuit in the ferroresonant or self-excitation state back to the desired state of operation, the corrective device should possess the following characteristics:

1. It should not operate before a pre-set voltage across the capacitor is reached (a figure of about 200 per cent voltage is an industry standard).
2. It should not operate prematurely. To do so would destroy the effectiveness of the capacitor on motor starts or rapid load changes.
3. It should completely eliminate some cases of ferroresonance and self-excitation and reduce the severity of otherwise sustained cases.
4. The device should be reliable and operate to achieve circuit stability.
5. It should be simple, compact, economical to produce, easy to attach and be made for outdoor operation.
6. It would be desirable to have some sort of adjustment to determine the degree of overvoltage operation.
7. It should return to the inoperative state after the abnormality has been cleared.

Two operating models of a corrective device were designed and constructed during the laboratory tests on ferroresonance and self-excitation. Both performed satisfactorily during tests to restore the circuit to the normal state. One model consisted of two silicon-controlled rectifiers, two solid-state diodes, a heat sink, and two, two-watt resistors. The function of the diodes and resistors was to make the device self-biased so that the use of a d-c source for the gate current was not needed. The other device consisted of a heat sink and the two silicon-controlled rectifiers and required a source of d-c current for control. A picture of the self-biased device is shown in Figure 5.1, and a schematic of it appears in Figure 5.2.

A silicon-controlled rectifier (SCR) is a semiconductor device which can be turned "on" anytime the anode is positive with respect to the cathode and will turn "off" at the end of each positive cycle of a-c voltage. The on period is adjustable, and the time taken to turn on is measured in degrees and is called the firing angle. No attempt is made here to explain the theory behind the operation of an SCR, but it is a current-controlled device whose firing angle is determined by magnitude and polarity of its gate current. In the two corrective devices mentioned above, the gate current was adjusted so the SCR's would operate when the voltage across the capacitors reached 30 volts.

Tests and Test Results

The first test performed involving the SCR corrective device was to see if it would quench a severe case of ferroresonance. It has been observed during earlier tests that a very severe case of ferroresonance would develop if the primary circuit contained 320 μf of capacitance, no lumped resistance, and was excited with about 220 volts. The secondary circuit was open for all tests on ferroresonance. A circuit of the above description was used with the SCR device connected across the capacitors. No high distorted currents were observed while the device was connected to the capacitors; but when the device was removed, the circuit quickly returned to the ferroresonant state and the protective fuse operated to de-energize the circuit. Several other tests were made as the applied voltage and capacitance was changed. No

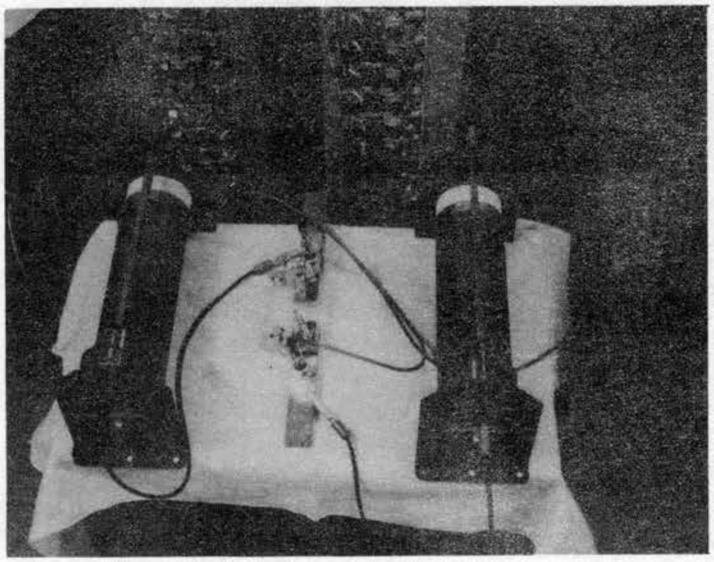


Figure 5.1. Self-Biased SCR Corrective Device

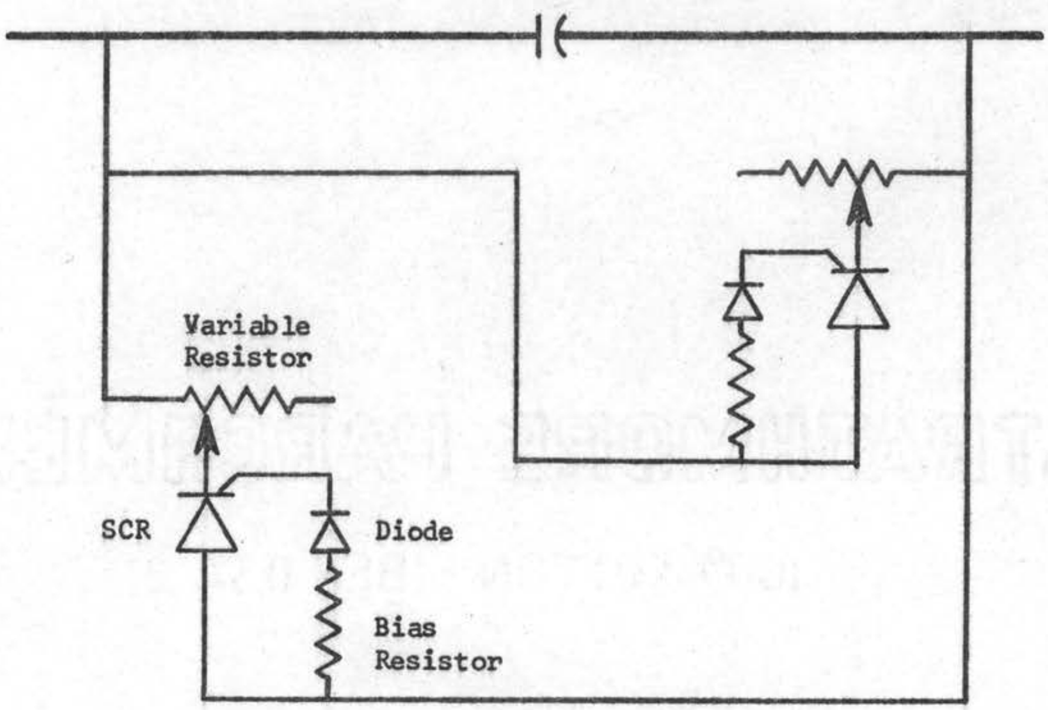


Figure 5.2. Circuit Diagram for Self-Biased SCR Corrective Device

ferroresonance was observed. On several occasions the primary-circuit ammeter indicated that ferroresonance currents were initiated with the closing of the switch but were quickly damped by the corrective device.

Figure 5.3 and 5.4 show the results of a "before" and "after" test on a circuit containing 3.4 ohms of lumped resistance and 320 μf of capacitance with an applied voltage of 185 volts. The trace shown in the two pictures is the voltage across the capacitor. The trace in Figure 5.3 shows the circuit in a mild state of ferroresonance. The waveform is distorted, and the voltage across the capacitor was much more than desired. Figure 5.4 shows the voltage waveform across the capacitor after the SCR device was connected across the capacitor. The waveform has been improved and the total voltage substantially reduced.

The next series of tests was designed to determine the effect of the SCR device on self-excitation. The circuit parameters were adjusted so that the motor, when energized, would go into a state of self-excitation. Figure 5.5 shows the primary current I_p (top trace), capacitor voltage V_c (second trace from top), voltage across both transformer and capacitor $V_{T + C}$ (third trace), reference voltage V_{ref} (fourth trace), and motor speed S (bottom trace). The circuit was excited with 210 volts and contained no lumped resistance but had a lumped capacitance of 156 μf shunted by the SCR device. The motor was loaded to 4.2 foot pounds of torque and drew a current of 6 amps. Because of the severity of self-excitation, the SCR's had to "fire" a number of times each cycle to keep the voltage across the capacitor at the desired level. When the device was disconnected from the capacitor in this test, the motor slowed down in speed and began to vibrate intensely. The wave shapes became quite distorted, and the

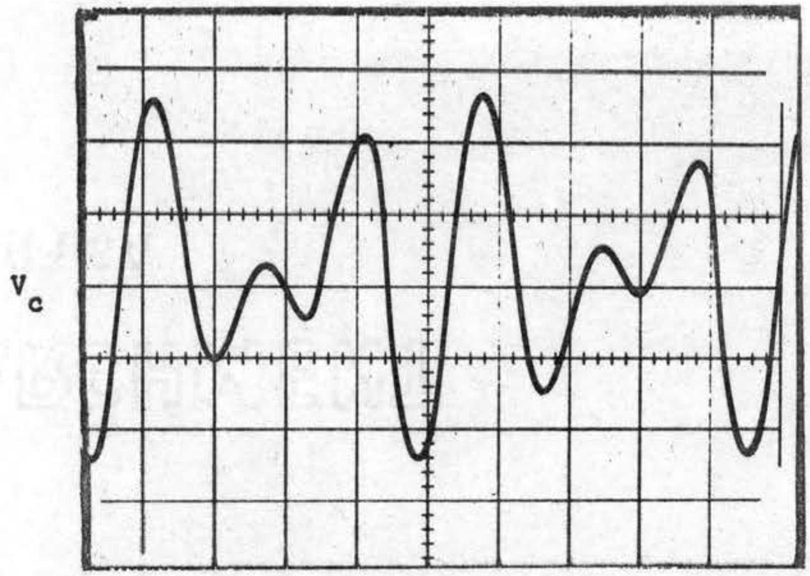


Figure 5.3. Capacitor Voltage for A Circuit in the Ferroresonant State

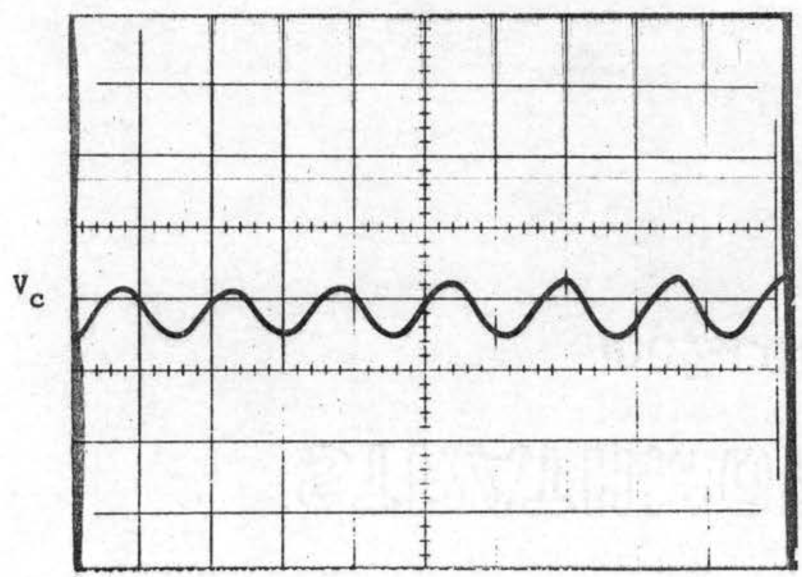


Figure 5.4. Capacitor Voltage After SCR Device was Attached

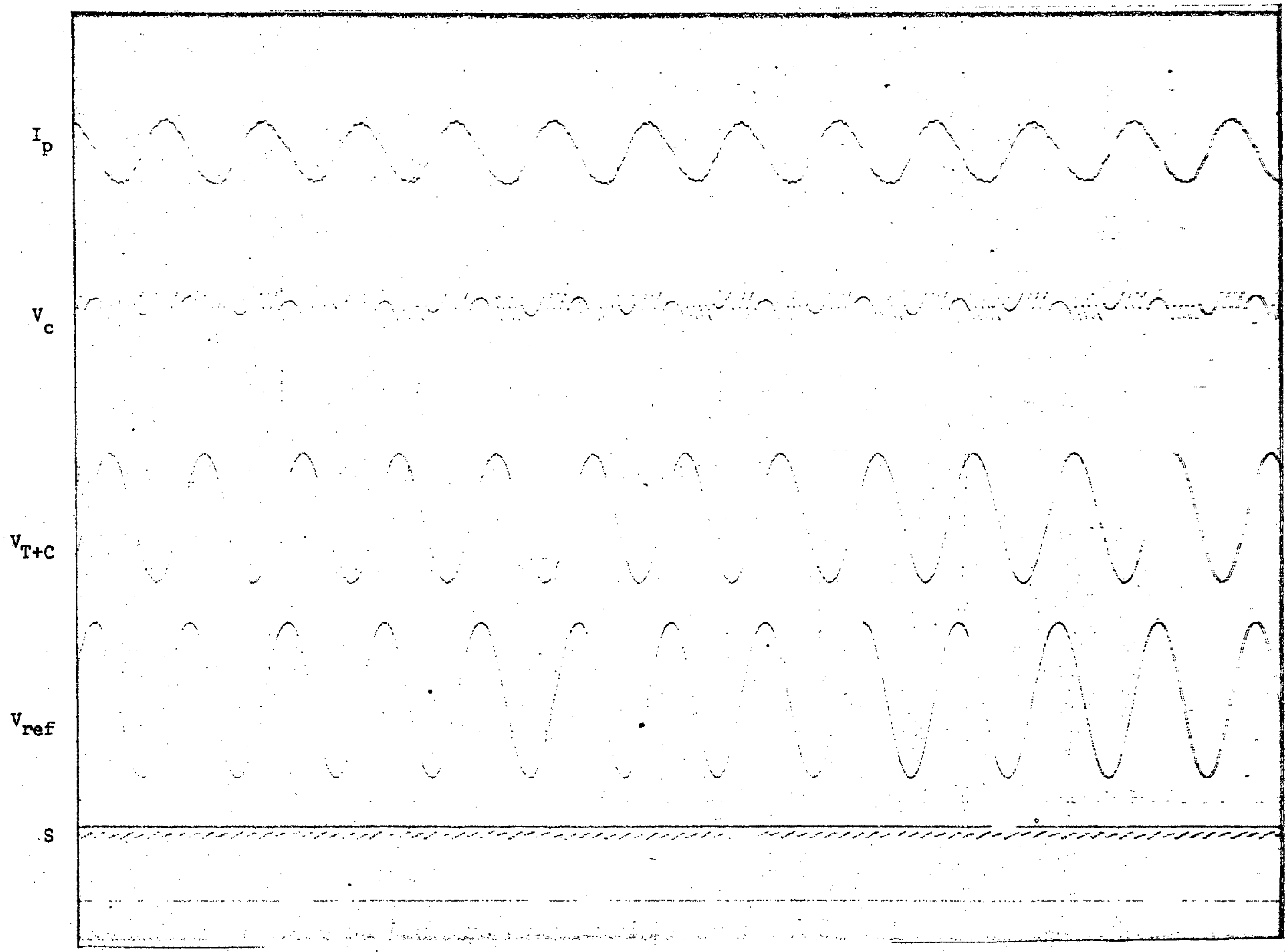


Figure 5.5. Motor Behavior While Loaded With SCR Device Shunting Capacitors

motor began to draw excessive current. Had the motor been left in this condition, the overload protective device in the motor windings would have operated to prevent motor damage. Had the SCR device been left connected across the capacitor, the motor would have continued to operate without interruption. There appears to be a slight distortion in the current wave shape of Figure 5.5, but the current does resemble a sinusoid which is the desired shape. The third trace $V_{T + C}$ indicates there is no saturation of the transformer which again shows that the operation is in the low-current region of the characteristic curves. The motor was operating very smoothly and quietly as indicated by the speed trace.

Figure 5.6 shows the results taken of a motor operating in a reduced state of self-excitation where the motor could not be started without the aid of the SCR device. It is obvious from the traces in the figure that there remains considerable distortion in the waveforms, but from all physical appearances the operation of the motor was normal. That is, there was no vibration, and the motor ran quietly and smoothly as if the capacitors had been removed from the circuit. The voltage drop across the capacitor V_C indicated that some regulation was still being maintained by the capacitors.

The traces in Figure 5.7 are for a normal state of motor operation. The circuit contained 420 μf of capacitance with an applied voltage of 195 volts. There was no shunting device of any sort across the capacitors. This chart indicates that as capacitance is added (beyond a certain value) the motor will be less susceptible to self-excitation.

Figure 5.8 and 5.9 show very well what effect the SCR device has in reducing self-excitation. In both charts the capacitors were

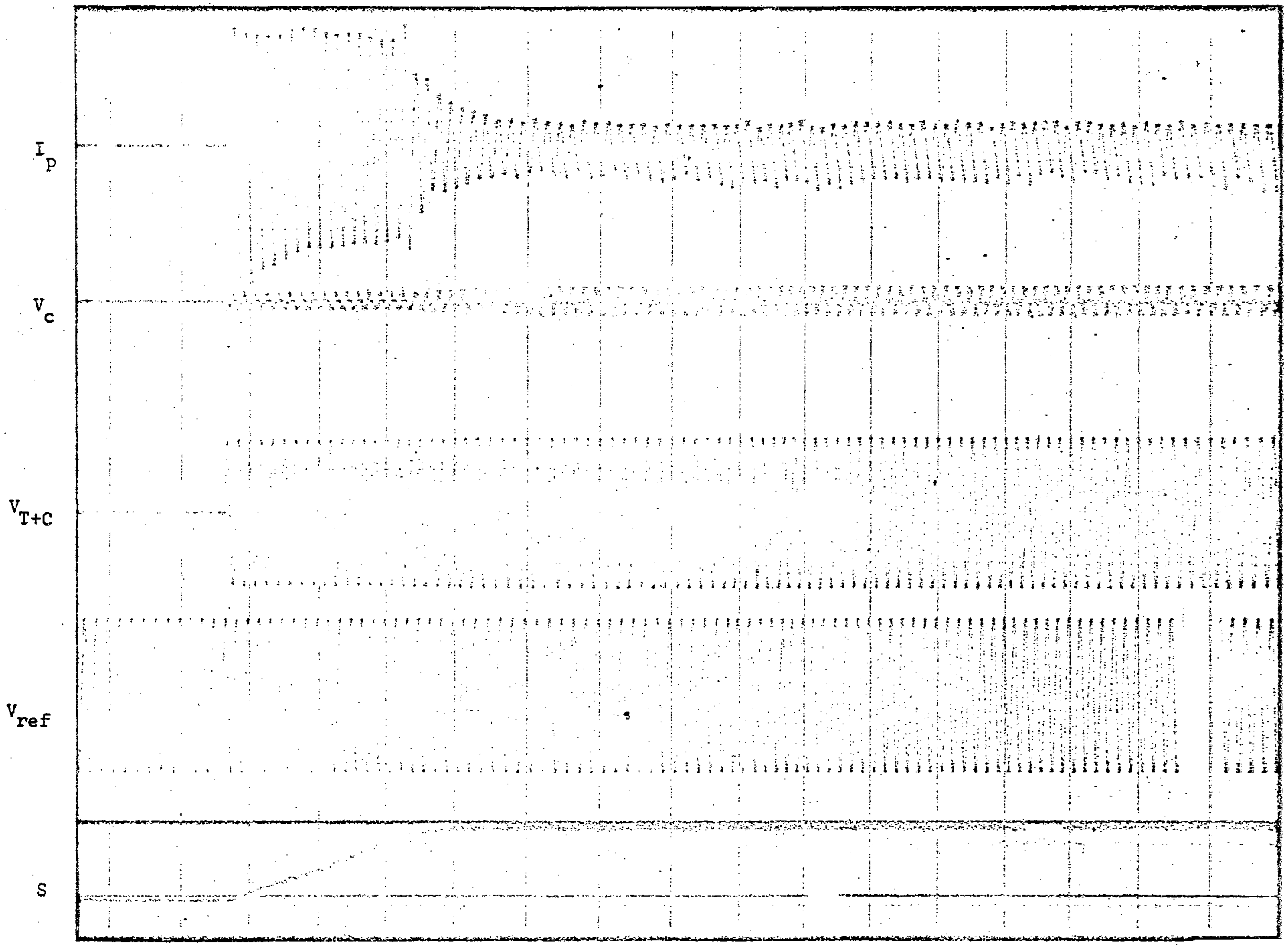


Figure 5.6. Motor Operation in a Reduced State of Self-Excitation

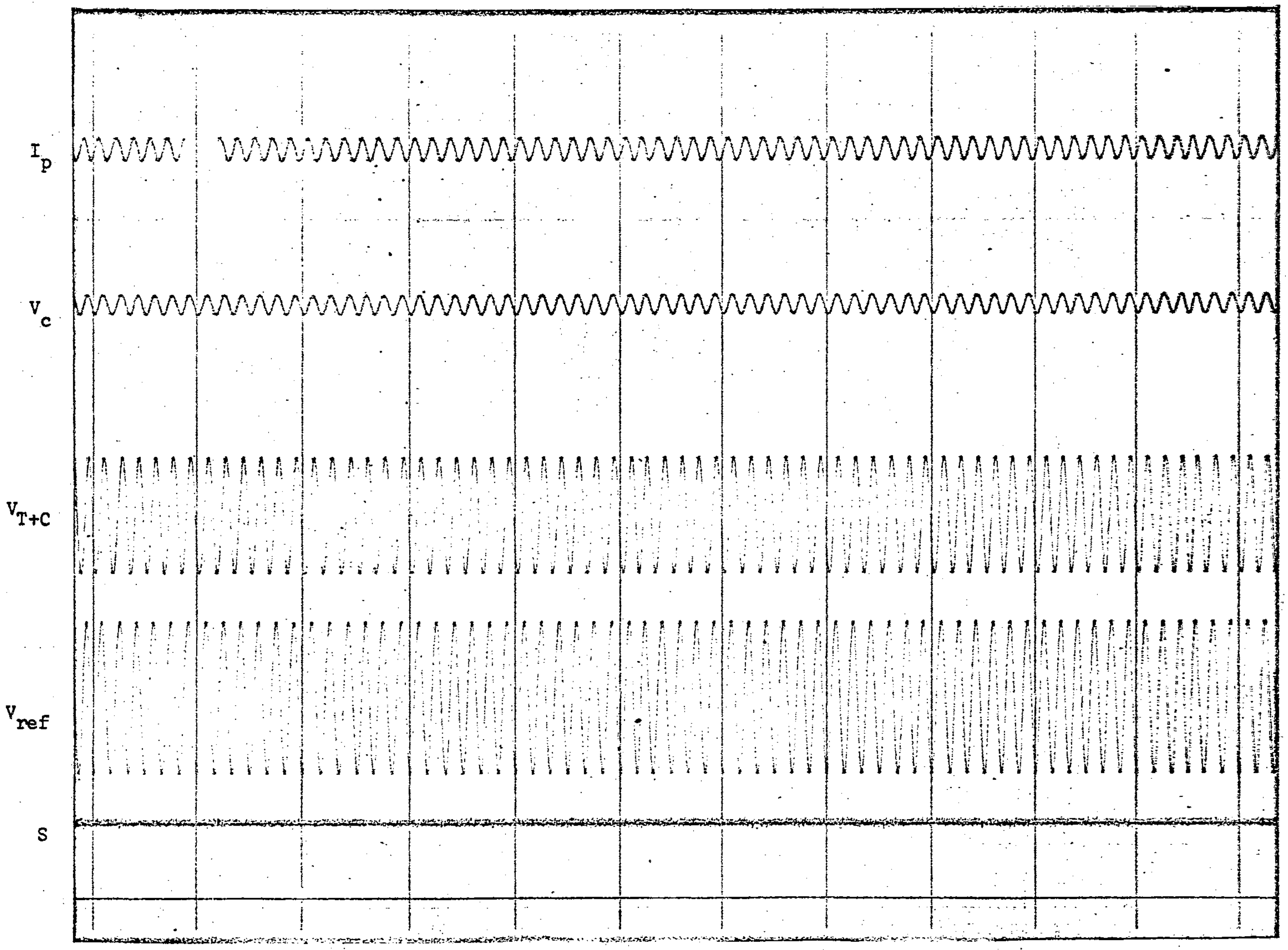


Figure 5.7. Normal State of Motor Operation

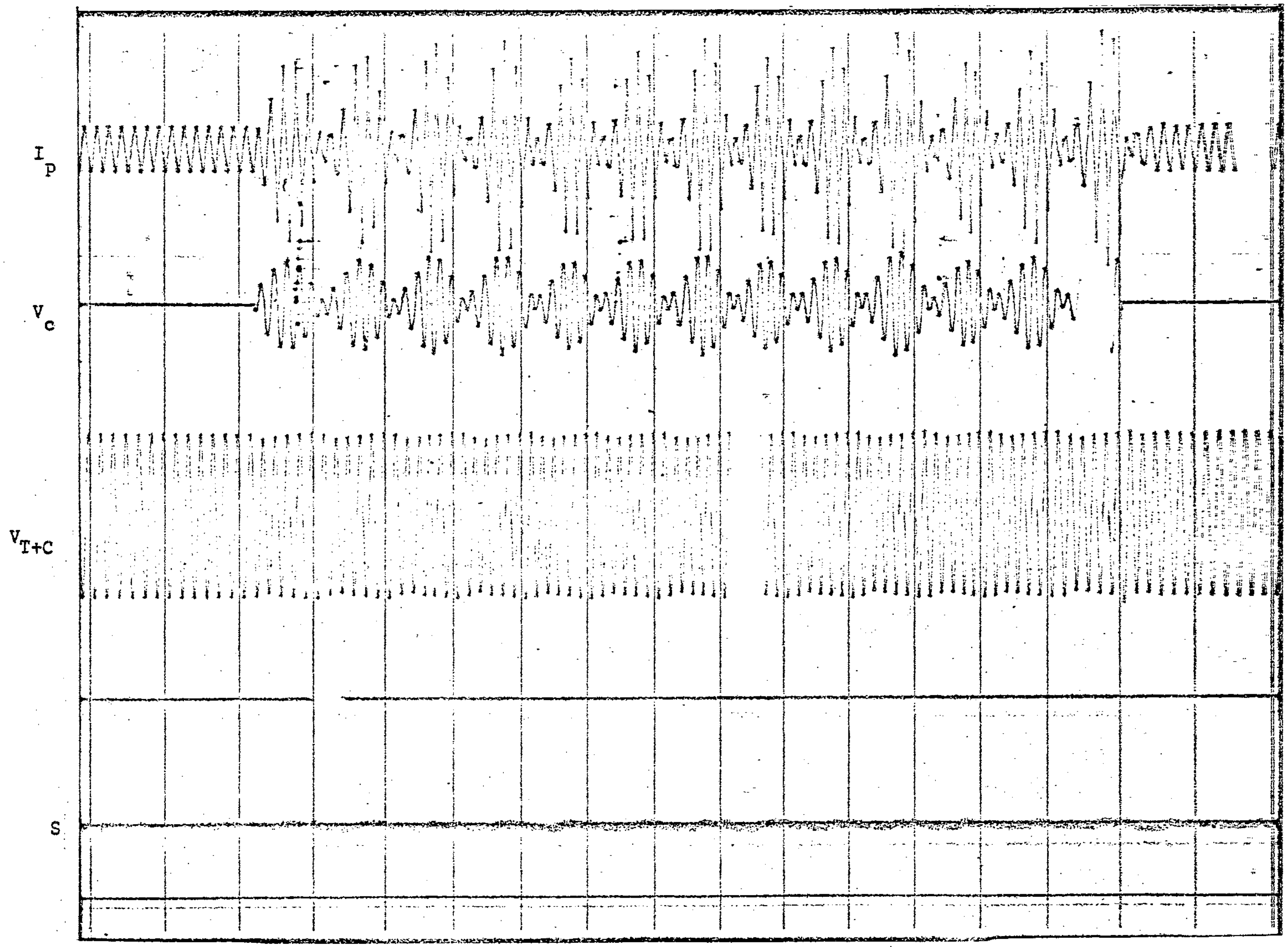


Figure 5.8. Motor Operation as Capacitor-Shorting Switch was Opened and Closed

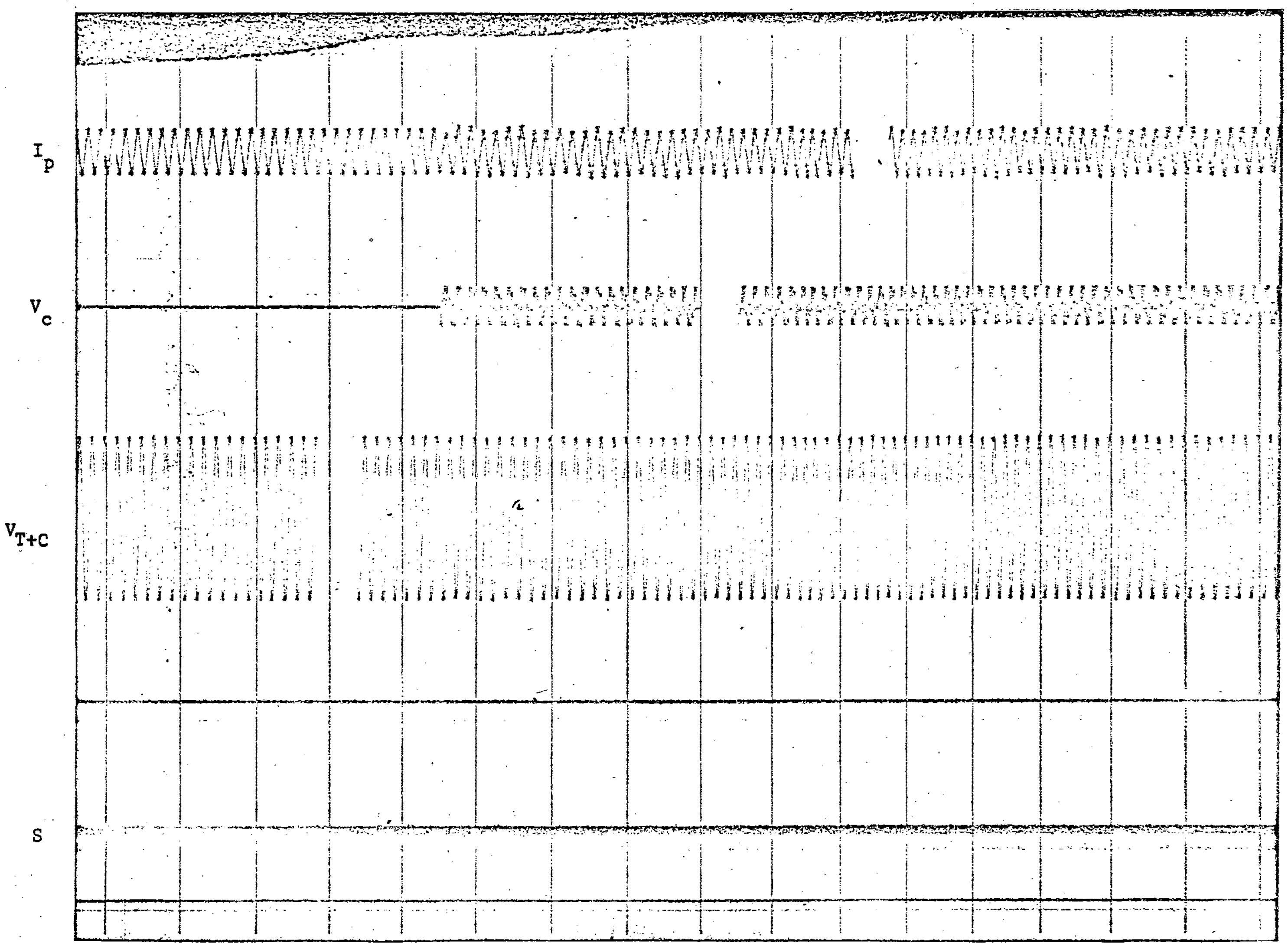


Figure 5.9. Motor Operation as Capacitor-Shorting Switch was Opened and Closed With SCR Device Connected

shorted with a switch for the first few cycles. The circuit parameters and voltage were the same, except the capacitors for the data in Figure 5.9 had the SCR's connected after the short was removed.

The next series of tests was designed to see if the shunting of the capacitors with the SCR device decreased the effectiveness of the capacitor to reduce the dip in voltage associated with the motor starting. Figure 5.10 is an oscillographic recording of the secondary or motor voltage V_m as the motor is switched on and accelerates. The amount of voltage drop associated with the starting of the motor can be seen about six cycles (point A) after the chart started recording. The percentage (peak to peak) voltage drop is about 20 per cent. This recording was for a circuit containing no capacitors. The second drop in the recording trace (point B) is that caused by the automatic removal of the start winding from the motor circuit. The value is about 25 per cent.

The oscillographic recording shown in Figure 5.11 was taken under the same conditions, except the capacitors were in the primary circuit. The amount of initial voltage drop (point A) was less (9 per cent) than in the previous figure, but the motor went into a state of self-excitation at start-winding switch speed and remained in that condition.

The circuit and loading conditions were the same for the recording shown in Figure 5.12, but in this case the capacitors were in the circuit and the SCR device was connected across them. The voltage drop associated with the initial starting was 13 per cent with a 20 per cent decrease at the moment the start winding switched out. As can be seen from the trace shortly after point B was reached, the machine began to start into self-excitation but was brought out and up to rated speed

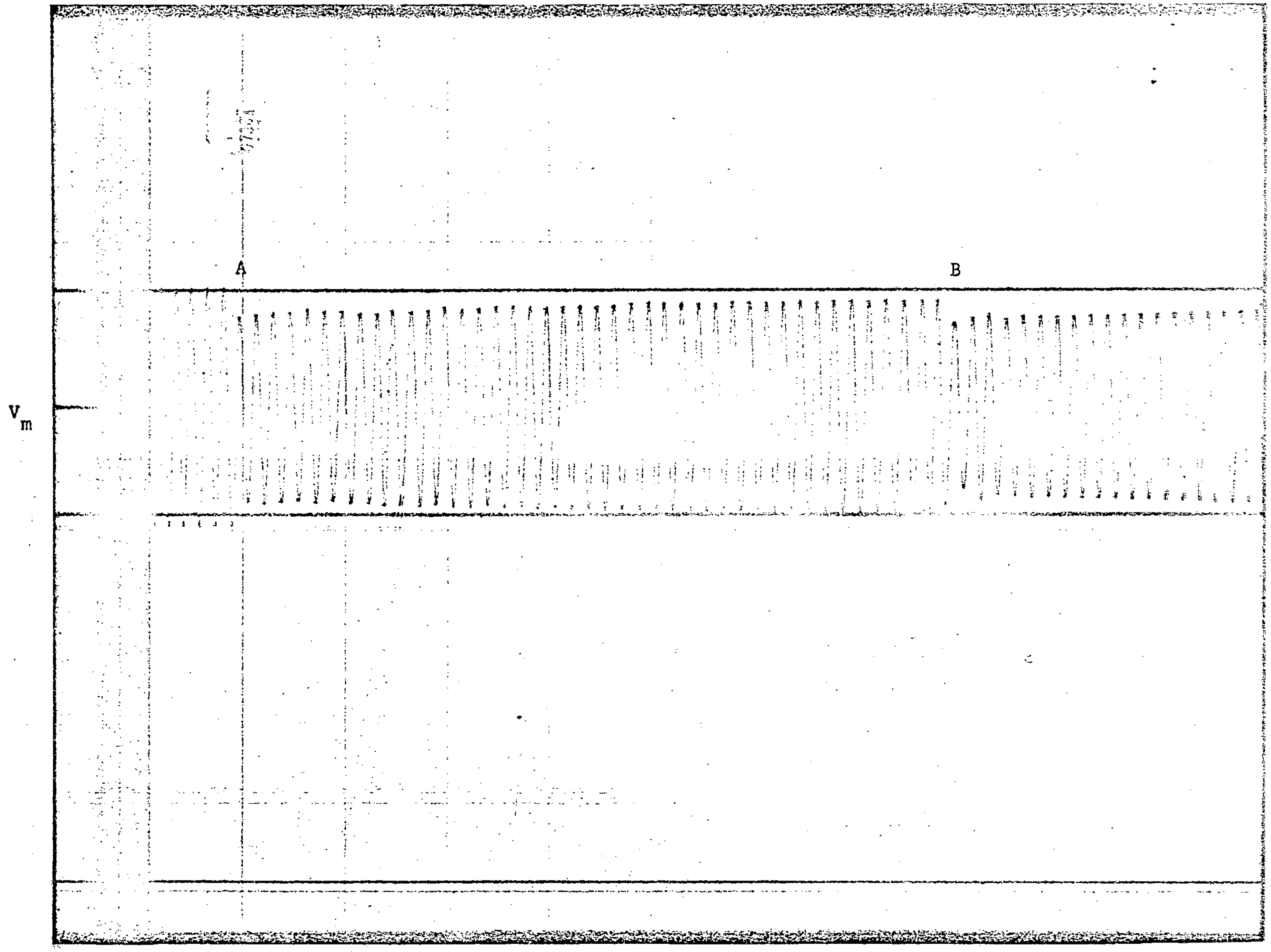


Figure 5.10. Motor Voltage as Motor is Switched on

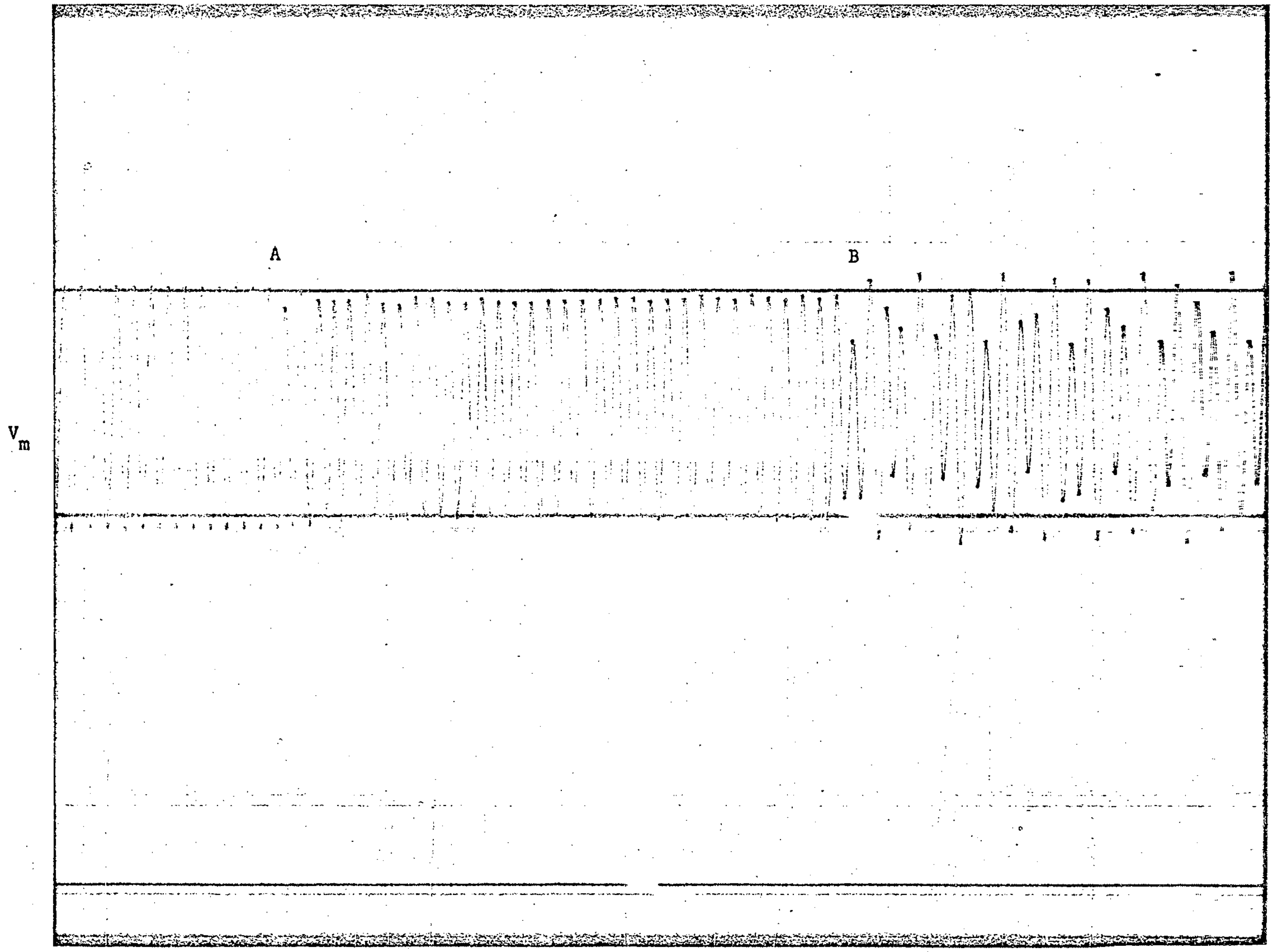


Figure 5.11. Motor Voltage as Motor is Switched on with Capacitors in Primary Circuit

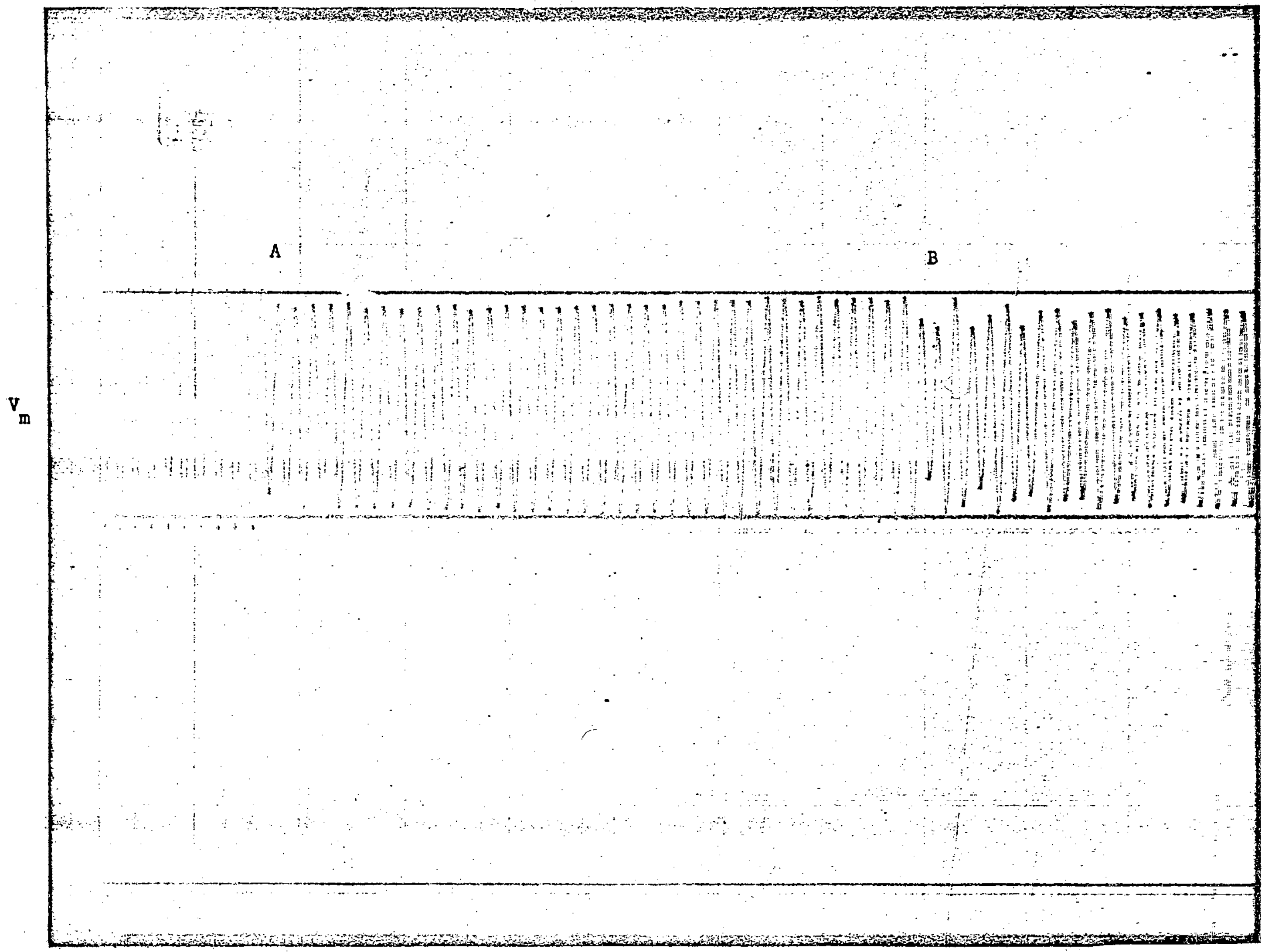


Figure 5.12. Motor Voltage as Motor is Switched on with Capacitors in Primary Circuit Shunted by the SCR Device

by the SCR device.

The recordings indicate that the SCR's do not take away the effectiveness but do reduce it slightly. Automatic regulation is still obtained by the capacitors which are now made stable by the SCR device. The device appears to fulfill the seven requirements listed earlier in the chapter. It is adjustable over a wide range of firing angles and provides the stabilization needed for proper motor and transformer operation. Being solid state, it is compact and can be installed anywhere a transformer can. It is believed that if mass produced the production costs would not be a prohibitive figure.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The added advantages of automatic voltage regulation and reduction or complete elimination of light flicker make the series capacitor more desirable in some capacitor applications than shunt-connected capacitors. Because of the instabilities associated with series-connected capacitors, a more thorough study of the circuit arrangement and parameters must be made.

The instability called ferroresonance generally has associated with it one or two stable operating states. The state in which a circuit operates depends on the amount of capacitance and resistance contained within the circuit, the shape of the reactor or transformer saturation characteristic, and the magnitude and switching angle of the applied voltage. It was shown in Chapter III that by varying either the applied voltage or the capacitance, the jump phenomena of ferroresonance can be obtained. If the transformer saturation curve, amount of capacitance, and circuit resistance are known, the points at which the circuit becomes unstable may be predicted through a graphical analysis of the circuit operation. The severity of ferroresonance depends on the circuit capacitance, resistance, and magnitude of applied voltage.

A type of instability associated with motor operation called self-excitation may be brought on by the use of series-connected capacitors in either the primary circuit of the transformer supplying the motor or the motor circuit. The condition may be recognized by the crawling of the motor and the large magnitude of motor current. It was found through testing that the motor current, capacitor voltage, and transformer voltage appeared to be modulated while the motor was in the self-excited state. The number of 60-cycle oscillations contained within the modulating envelope period proved to be a function of the load and the applied voltage.

The theory was advanced that the instability was produced by the oscillation of the circuit to and from the saturated and unsaturated states of the motor and transformer very much like the jump phenomena associated with the ferroresonant circuit. Through a graphical analysis similar to that used in Chapter III on the ferroresonant circuit, it was shown that the currents and voltages at which the motor went into a sustained high-current condition and a modulated condition could be predicted with some accuracy.

A new type of corrective device to eliminate or reduce the severity of ferroresonance and self-excitation was designed around the use of silicon-controlled rectifiers. The SCR device was tested on individual cases of ferroresonance and self-excitation. The test results indicated the device had performed satisfactorily to eliminate both conditions. On some tests in which the severity of the instabilities was very great (probably greater than would be found in actual practice), the SCR device reduced the severity of the instability, stabilized the circuit, and improved the waveform.

Conclusions

The problems encountered in the field during the high-voltage tests indicated that both ferroresonance and self-excitation should be achieved in the laboratory under low-voltage conditions before a high-voltage test could be successfully and efficiently performed. Even the fruits of the low-voltage laboratory tests were long in coming.

The accuracy of the graphical analysis made on the ferroresonant circuit proved the method to be useful in the application of series capacitors. Its simplicity and speed of application is also in its favor.

Although the graphical analysis made on self-excitation was not as accurate as that made on ferroresonance, it still could provide a useful tool in predicting the sustained high-current state and oscillatory state of such a circuit. Many more variables are introduced when a motor is added to the circuit. One of the more important facts brought out by this investigation was the effect the start winding had on the operating state the motor would finally achieve. The ability to manually open the start-winding circuit showed that the motor had insufficient accelerating torque at the start-winding switch speed while in a state of self-excitation to force the centrifugal switch open in order to disconnect the start winding. No doubt the changing of the motor circuit impedance when the start winding was disconnected manually caused the motor torque characteristic to change enough to accelerate the motor on up to rated speed. It is believed that the voltage drop in the circuit resistance associated with the oscillations in current and the dynamic characteristics of the composite motor-transformer, volt-ampere curve help to produce the modulating effect.

The distortion in the wave shapes recorded during some self-excitation conditions indicates that there are subharmonics existing in the circuit. The Fourier series coefficient program run on the digital computer (see Appendix B) revealed that for the particular wave shape analyzed the subharmonic content was quite large. There is no doubt in the writer's mind that subharmonics do exist in the circuit (at least for some degrees of self-excitation), but it is not known whether these subharmonics are produced by generator action or by operation in the nonlinear region of the volt-ampere characteristic. It is quite obvious from inspection of the speed trace in the oscillographic recordings and the degree of vibration produced by the motor that forward and backward torques are produced synchronously with the modulating envelope variations. The acceleration and deceleration periods indicate that these torques are extremely large.

Another observation made during the tests showed that a circuit containing a series capacitor in its primary could be shocked so severely by the starting of a motor in the secondary that the primary-fuse element would blow due to large ferroresonance currents before the motor could attain even start-winding switch speed. It was found that a large value of lumped-primary resistance prevented this problem from occurring.

Probably the most rewarding outcome of the entire investigation was the invention of a new type of corrective device for reducing or eliminating ferroresonance and self-excitation. The device was applied and tested many times under varying degrees of these instabilities and was found to be both effective and reliable in reducing the circuit to a stable state of operation. It is evident after some study of the motor voltage traces appearing in Figure 5.10, 5.11, and 5.12 that the SCR corrective device produces circuit stability but not at the expense of voltage regulation. The capacitors still operate to provide automatic voltage regulation. Little or no losses are associated with the device, so its advantage over the use of resistors to damp out self-excitation and ferroresonance is very real.

Much effort remains to be made in perfecting this device, and this is one area of future work associated with this investigation. Further investigation should be made to determine if the subharmonics appearing in the current and voltage waveforms are caused by generator action, operation in the nonlinear region of the volt-ampere characteristic, a combination of the two, or something entirely different. An electromechanical simulator could be made to try to reproduce the modulating envelope evidenced in the many traces which were recorded.

If a true simulation of a single-phase motor could be produced, an analog computer analysis of the problem would be very rewarding. The simulation of the motor would be very difficult but should include the energy-storage elements both mechanical and electrical.

This problem is most complex to solve analytically, but every effort should be made to keep up with the advances in mathematics so that a complete solution for such a practical problem will someday be achieved to the satisfaction of the power distribution engineer.

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APPENDIX A

The data for the 3 kva transformer saturation curve were obtained by boosting the applied voltage to the transformer primary with a 220-volt variac and 1:2 ratio transformer connected in parallel. The variac voltage was varied from zero and the following data recorded from direct indicating meters.

TABLE A1

SATURATION CURVE DATA FOR 3 KVA TRANSFORMER

Transformer Primary Voltage in Volts	Transformer Primary Current in Amperes
100	0.2
150	0.3
175	0.3
200	0.5
220	0.6
250	1.0
270	2.0
290	5.4
300	7.1
310	14.0
320	16.5
330	20.0
333	24.0

Data for Table A2 and Figure 4.10 were taken like that appearing in Table A1, except the motor was energized by the transformer secondary circuit.

TABLE A2

VOLT-AMPERE DATA FOR A 3 KVA TRANSFORMER AND A 3/4 HP CAPACITOR-START INDUCTION MOTOR OPERATING AT RATED R.P.M.

Transformer Primary Voltage in Volts	Transformer Primary Current in Amperes
50	0.2
100	0.4
150	1.0
200	2.5
220	3.0
240	4.0
260	6.1
280	7.2
300	11.0
320	17.0
330	25.0

Data for Table A3 and Figure 4.10 were taken with the same equipment arrangement as that for the data in Table A2, but the motor rotor was locked.

TABLE A3

VOLT-AMPERE DATA FOR A 3 KVA TRANSFORMER AND

A 3/4 HP CAPACITOR-START INDUCTION

MOTOR WITH LOCKED ROTOR

Transformer Primary Voltage in Volts	Transformer Primary Current in Amperes
50	3.0
100	8.5
150	14.0
200	20.0
215	22.0
240	25.0

APPENDIX B

Figure B1 shows an oscilloscope picture taken of a motor in a state of self-excitation. The top trace is primary current I_p, and the bottom trace is motor current I_m. The picture was enlarged to permit a more accurate measurement of amplitudes which could be used in a digital-computer analysis of the waveform.

Due to the nature and apparent repetition of the waveform, it was decided to analyze the waveform for subharmonic content. Since no known program for computing subharmonics on a digital computer was available, the writer decided to use the "Fourier Series Coefficients Simpson's Rule Integration" program of the Oklahoma State University Engineering Computer Laboratory library. The program had been written to compute the fundamental and higher harmonics. In order to utilize the program, the writer had to choose the lowest suspected subharmonic and use that as the fundamental for the program. Since the wave shape appeared to have a period every fifth cycle of 60-cycle oscillation, a fundamental of 16 cycles or 1/5 subharmonic of 60 cycles was used. The computed values would have 24 cycles as a second harmonic, 36 cycles as a third harmonic, and so on to the maximum number of harmonics desired. The program was asked to calculate 15 harmonics.

The period was divided into 116 equal time intervals, and 117 ordinate values corresponding to the amplitude of the wave shape were measured and punched onto data cards. These values appear in Table B1.

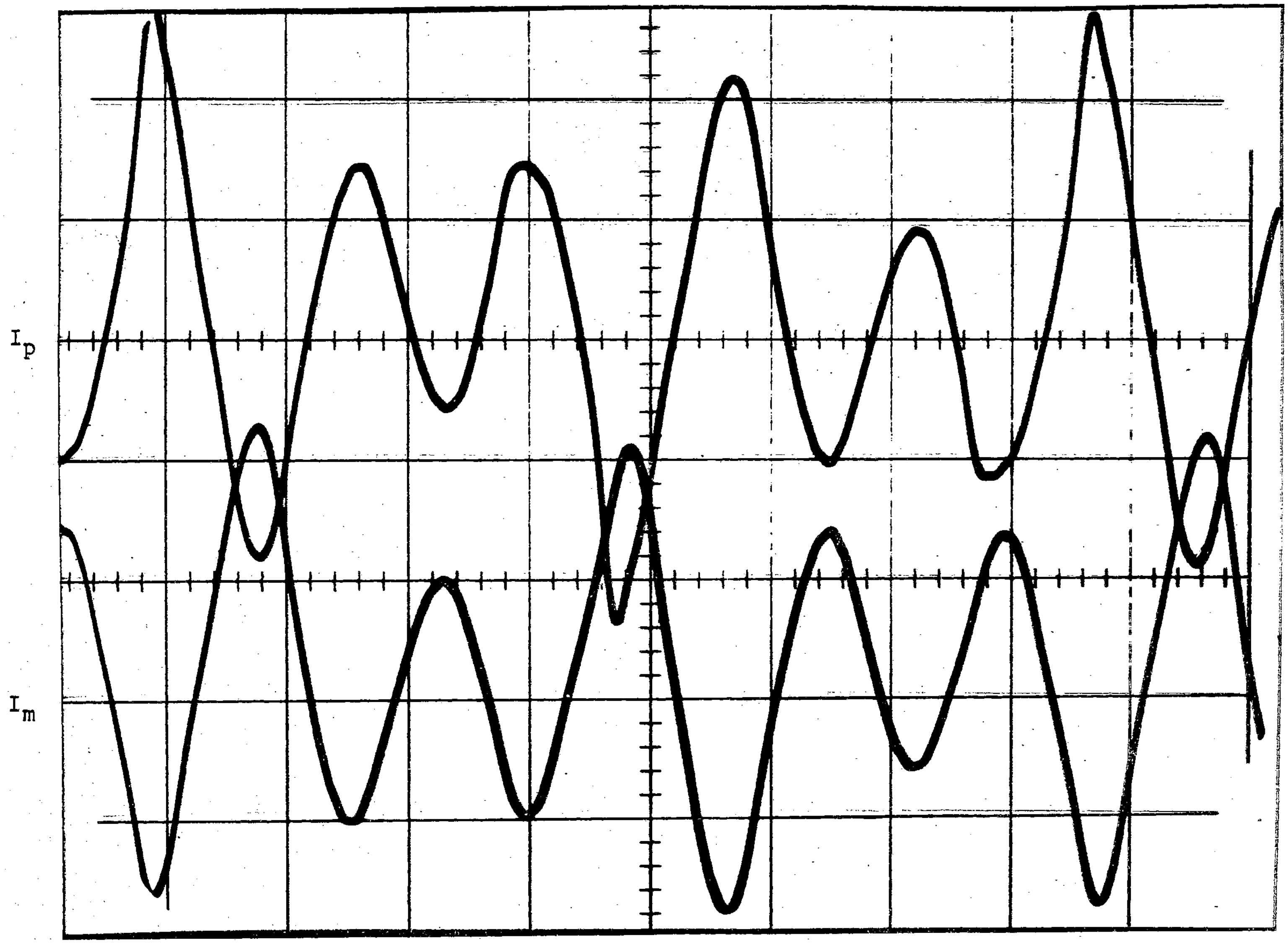

Figure B1. Primary and Motor Current of a Motor in a State of Self-Excitation

TABLE B1

DATA POINTS CORRESPONDING TO 116 TIME INTERVALS FOR

FOURIER SERIES COEFFICIENT PROGRAM

	117	15				
19.0	18.0	16.0	13.5	9.0	6.0	4.0
0.0	-3.0	-6.0	-9.0	-12.0	-14.0	-15.0
-15.5	-14.5	-12.5	-9.0	-7.0	-3.0	0.0
2.0	5.0	6.5	8.0	9.0	9.0	8.0
7.0	5.0	3.0	1.0	-1.0	-2.5	-4.0
-5.5	-6.0	-6.0	-5.5	-4.0	-2.0	0.0
2.0	6.0	8.0	9.0	9.0	9.0	8.0
7.5	4.0	4.0	1.5	-1.5	-4.0	-8.0
-14.0	-18.0	-19.0	-17.0	-15.0	-12.0	-9.0
-6.0	-2.5	0.0	2.5	5.0	9.0	11.0
13.0	14.0	14.5	13.5	12.0	8.0	5.0
2.0	0.0	-3.0	-5.0	-7.0	-8.0	-9.0
-9.0	-8.5	-7.0	-5.0	-3.5	-2.0	0.0
2.0	3.5	4.0	5.0	5.0	4.5	3.0
1.0	-1.0	-3.0	-7.0	-9.0	-10.0	-10.0
-10.0	-9.0	-8.0	-6.0	-4.0	-2.0	0.0
3.0	6.0	11.0	16.0	19.0		

The output of the program is shown in Table B2. The columns headed A, B, and C are the Fourier series coefficients, and column 5 is the phase angle associated with the C coefficient. If the last column is normalized to correspond to 100 per cent of 5th harmonic (60 cycles), one of the subharmonic coefficients appears to be noticeable. The third harmonic (3/5 subharmonic of 60 cycles) has a coefficient value of 0.44 compared to 1.0 for the 5th harmonic (60-cycle fundamental). This implies that the wave shape, according to the computer program, has a very large 36-cycle subharmonic. The other subharmonics are two per cent or less.

TABLE B2

OKLAHOMA STATE UNIVERSITY ENGINEERING COMPUTING LABORATORY

FOURIER SERIES COEFFICIENTS

SIMPSON'S RULE INTEGRATION

Average Value = -.33

Number of Harmonic	A	B	C	Phi Deg.	Per Cent Harmonic
1	.07	.21	.22	18.65	100.00
2	.03	.13	.13	15.20	62.46
3	4.62	-1.58	4.88	-71.14	
Error F8 .21961309E+04					
4	.16	.09	.19	60.11	85.59
5	10.20	3.72	10.86	69.96	
Error F8 .48778110E+04					
6	-.05	.25	.26	-12.65	117.81
7	.62	.16	.64	75.51	288.23
8	-.03	.13	.13	-13.10	61.53
9	.29	.05	.29	78.85	133.44
10	-.04	.18	.19	-12.16	86.35
11	.90	.12	.91	82.13	412.02
12	-.03	.14	.14	-12.09	66.45
13	.95	.04	.95	88.67	429.27
14	.01	.09	.09	9.18	44.08
15	.34	.05	.34	81.21	155.91

VITA

Marion Earl Council

Candidate for the Degree of

Doctor of Philosophy

Thesis: AN EXPERIMENTAL INVESTIGATION OF SELF-EXCITATION ON 60-CYCLE, SINGLE-PHASE POWER CIRCUITS

Major Field: Engineering

Biographical:

Personal Data: Born in Palmetto, Florida, May 20, 1929, the son of Charles T. and Verter S. Council.

Education: Attended grade school in Palm View, Florida; graduated from Palmetto High School, Palmetto, Florida, in 1947; received Bachelor of Science Degree with a major in Electrical Engineering from the University of Florida in June, 1957; received the Master of Science Degree with a major in Electrical Engineering from the Louisiana State University in June, 1960; completed requirements for the Doctor of Philosophy Degree in May, 1965.

Professional Experience: Employed by Gulf States Utilities Company in Baton Rouge, Louisiana, as a Transmission and Distribution Engineer from June, 1957, to September, 1960; Instructor in the Electrical Engineering Department of Louisiana State University during the academic year of 1960-61 and 1961-62; Consulting Engineer for Albert Switzer and Associates in Baton Rouge, Louisiana, during the summer of 1961; Research Participant at Oak Ridge Nuclear Laboratory at Oak Ridge, Tennessee, during the summer of 1962; Instructor in the Electrical Engineering Department of Oklahoma State University at Stillwater, Oklahoma, from September, 1962, to January, 1965; Assistant Professor at Louisiana State University from January, 1965, to the present.

Membership in Scientific and Professional Socities: Registered Professional Engineer in Louisiana; Member of the Institute of Electrical and Electronic Engineers; Professional Member of Eta Kappa Nu.