THE ELECTRICAL CHARACTERISTICS

of the

DIRECT CURRENT WELDING ARC

and the

DESIGN and TESTING

of a

D.C. WELDING GENERATOR

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SUMMARY

The machine to be used as the power source is first evaluated by means of the usual indirect tests. These tests confirm that the machine has acceptable steady state characteristics for welding and a basic excitation control circuit is employed to give the desired control of the output from the generator.

The initial welds made are very unsatisfactory and attempts to improve the weldability by modifying the characteristics of the control circuit are unsuccessful. Only by increasing the time constant of the output circuit through the addition of series inductance can the desired improvements be obtained.

At this stage an investigation into the electrical characteristics of the D.C. welding arc is carried out. This reveals the extreme transient nature of the arc load on the generator and design criteria for good weldability can now be employed to achieve satisfactory results.

Field excitation of the alternator is varied by means of current feedback from the output circuit which is able to produce high welding currents when using a low voltage reference supply from a battery.

The initial evaluation has to be repeated on a new design of alternator and tests indicate that a suitable A.C. reactor in the output from the alternator will produce a more desirable transient response to the arc load.

Different types of current control are tried in order to obtain the best type and range of welding characteristics.

The design of the most important components which make up the welding generator is discussed and the proposed layout for the complete set is given.

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1. I N T R O D U C T I O N

1.1 THE OBJECTIVE

The purpose behind the research carried out in this thesis is to produce a transportable source of electric power which can be used to provide either:

(a) 3-phase, 380 volt A.C. power supply or

(b) 400 amp D.C. arc welding supply, but both from the same unit.

The advantages and uses of this type of power unit would be for field and construction site work, where a compact dual purpose supply is required at a moderate cost to the contractor. The utility factor of this type of machine is considerably higher than for two separate units, thus giving more value for money.

1.2 THE GENERATING SET

The power source or generating set is to be made up of a diesel driving engine directly coupled to an A.C. generator; which is commercially available in the form of a self exciting, self regulating, 3 phase alternator.

In order to extend the capabilities of this plant it is intended to design a suitable control system so that the generator may also be used for D.C. arc welding when required. It will thus be necessary to have two sets of controls, for A.C. power or D.C. welding and a simple switching mechanism for selecting either supply, with adequate protection for the operator. The controls are to be mounted in a partitioned cubicle, one half for power and the other half for welding, and the cubicle positioned in a suitable place on the set. The whole set will be mounted on a four wheeled trailer or skids for transport on the back of a truck.

1.3/...

1.3 MECHANISM OF WELDING

A detailed description of the process of Shielded Metal-Arc Welding is not required here but briefly it involves the deposition of metal from a filler rod or electrode to the parent metal or work, by means of the heat generated and forces set up in the formation of an electric arc. The control of three variables is important in the application of metal-arc welding. These are speed of travel, amperage and arc voltage. The operator controls the speed of travel and the arc voltage while welding manually, but the current control is a property of the machine and depends on the setting for a particular job. Other factors affecting the chemical, metallurgical and mechanical variables involved in the welding process will not be discussed here as the operator has little control over these factors which largely depend on the type of material used to make a weld. Figure 1.1 illustrates the mechanism of weld metal deposition in the shielded metal arc.[1]

The electrical characteristics involved in the mechanism of arc welding do however play an important part in the design of the equipment used in the welding process and much of the research carried out for this thesis is concerned with producing a welding generator with suitable electrical characteristics. These characteristics are further described in the following sub-section.

1.4 DESIRED ELECTRICAL CHARACTERISTICS

In order to clarify the factors involved in obtaining the correct electrical characteristics from the welding generator these characteristics are divided into two sections as follows:

(a)/...

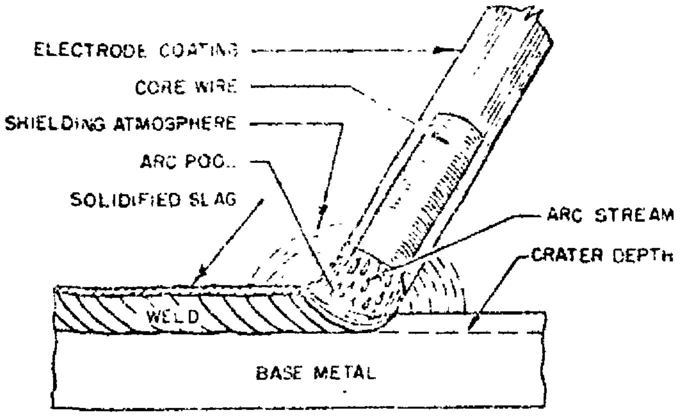


Fig. 1.1 Weld Metal Deposition.

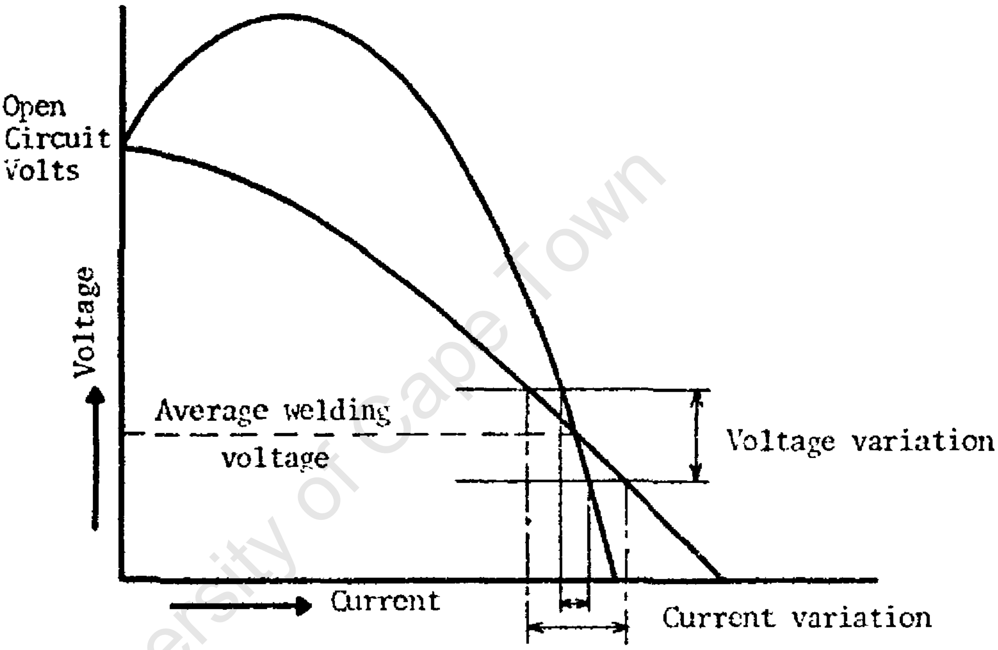


Fig. 1.2 Static Volt-amp Characteristics.

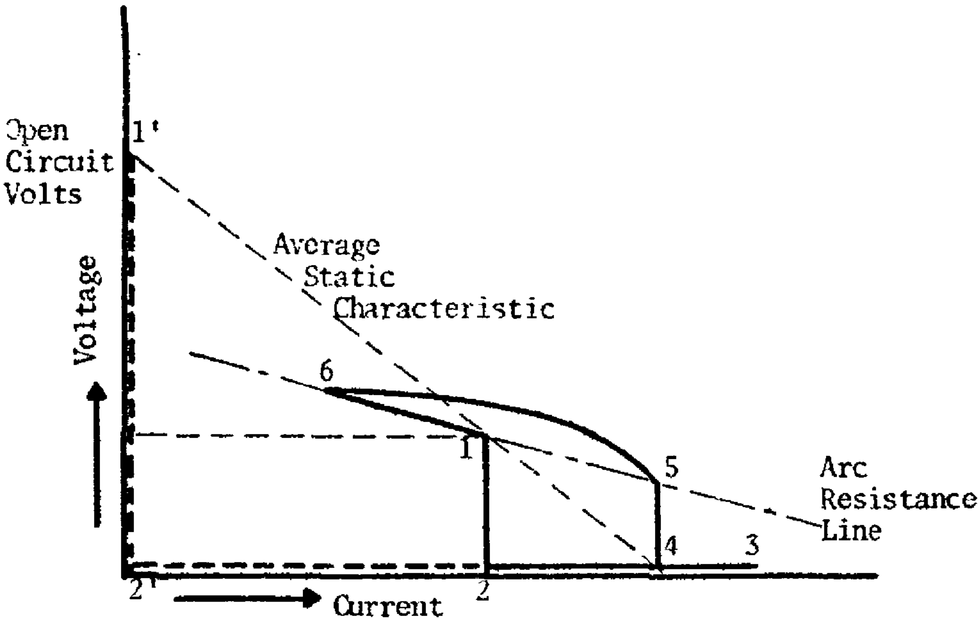


Fig. 1.3 Dynamic Volt-amp Characteristics.

(a) STATIC CHARACTERISTICS

These characteristics describe the response of the welding generator to a steady state resistive load and are controlled or varied by means of the voltage and current adjustments provided on the unit. For a single operator D.C. welding generator the usual type of characteristic required is a constant current characteristic over the normal range of welding arc voltages. This implies that there should be a small current charge for varying arc voltages between 20 and 40 volts for each current control setting over the range of welding currents available from the machine. Fig. 1.2 shows typical static volt-amp curves for a constant current D.C. welding generator and illustrates the fact that a steep characteristic produces a small current charge over the range of normal welding-arc voltages. This type of characteristic is desirable as it is impossible for the operator to hold a constant arc length and the arc length determines the arc voltage during welding. As rapid current charges cause unsatisfactory spatter and metal deposition it is advisable to have minimum current charge for varying arc voltages and thus a drooping characteristic is essential for satisfactory welding with a manually controlled arc. This is not as critical for automatic welding machines where the arc length is precisely controlled by an automatic feed mechanism. Actual tests have shown that the melting rate of welding electrodes is directly proportional to the current and almost independent of the arc voltage.[1]

Thus the static characteristics for the welding

generator/...

generator in question are to be of the constant current type, described above.

(b) DYNAMIC CHARACTERISTICS

The steady-state characteristics previously described determine the operating point of the welder. However they have little to do with the weldability and actual performance of the welding generator. The dynamic characteristics determine the arc stability and quality of the weld.

The most important factor which influences the dynamic characteristics of the welding machine is the manner in which the metal transfer between electrode and parent metal work piece takes place. The welding arc load is of a continuous transient nature and this affects the machine's characteristics in a number of ways.

Referring to Fig. 1.1 the metal transfer occurs in the form of globules of molten metal which can vary in size from small powder-like grains to large droplets or blobs of liquid metal. Some of these metal blobs are large enough to bridge the gap between the electrode and the work thus causing a short circuit of the arc and the corresponding fall, almost to zero, of the arc voltage. If the duration of the shorting of the arc by the metal drops is sufficiently long the arc can become unstable and be extinguished or snuff out. This of course is an undesirable and unacceptable characteristic which causes discontinuities and faults in the weld metal.

Fig. 1.3 shows a typical dynamic volt-ampere characteristic which illustrates how the current and voltage vary during normal welding operations when a metal drop short circuits the arc. The average welding conditions are represented by point 1 on the graph and point 1^1 represents the open circuit conditions before striking the arc. Points 2 and 2^1 are the instants of short circuit by the metal drop or the welding electrode. The arc current then rises abruptly and overshoots to point 3 determined by the machine's transient characteristics. When the current has fallen to point 4 the short clears and the voltage rises almost to the average welding voltage at point 5 in a very short interval. Before recovery to average conditions the current undershoots to point 6, again determined by the machine's transient characteristics and at this point the arc voltage is usually a maximum. The time interval between points 6 and 1 is dependent on the system recovery time constant determined largely by the constantsof the machine.

High current overshoots at point 3 cause increased metal spatter and low undershoots at point 6 result in an unstable welding arc.

The metallurgical and physical aspects of weld metal deposition and arc stability are not discussed in this thesis, but the electrical characteristics resulting from these factors are described in more detail in a later section. It is sufficient to say here that the arc stability is dependent on the open circuit and transient voltage recovery characteristics of the machine and also on the magnitude of the current undershoot and overshoot which occurs when the arc is short circuited by a molten metal drop.

2. MACHINE AND GENERATING PLANT

2.1 DESCRIPTION OF THE MACHINE

The machine used as the basic power source is the comparatively new type of A.C. generator, the brushless alternator. The slip rings and brushes normally employed in providing the D.C. excitation for the rotating field winding have been replaced by a separate A.C. exciter, the output of which is rectified by diodes mounted on the shaft and the resulting D.C. fed to the main field winding. These machines are commercially available and the one used here is taken from the 'Markon' range of industrial brushless A.C. generators.

The stator windings are brought out to the main terminal connecting panel thus enabling any standard voltage to be obtained by varying the connections made at the terminals. As the voltages required for arc welding are much lower than for the 3-phase A.C. supply, and the output current for welding is to be as high as possible, the stator windings have to be reconnected when the generator is used for welding.

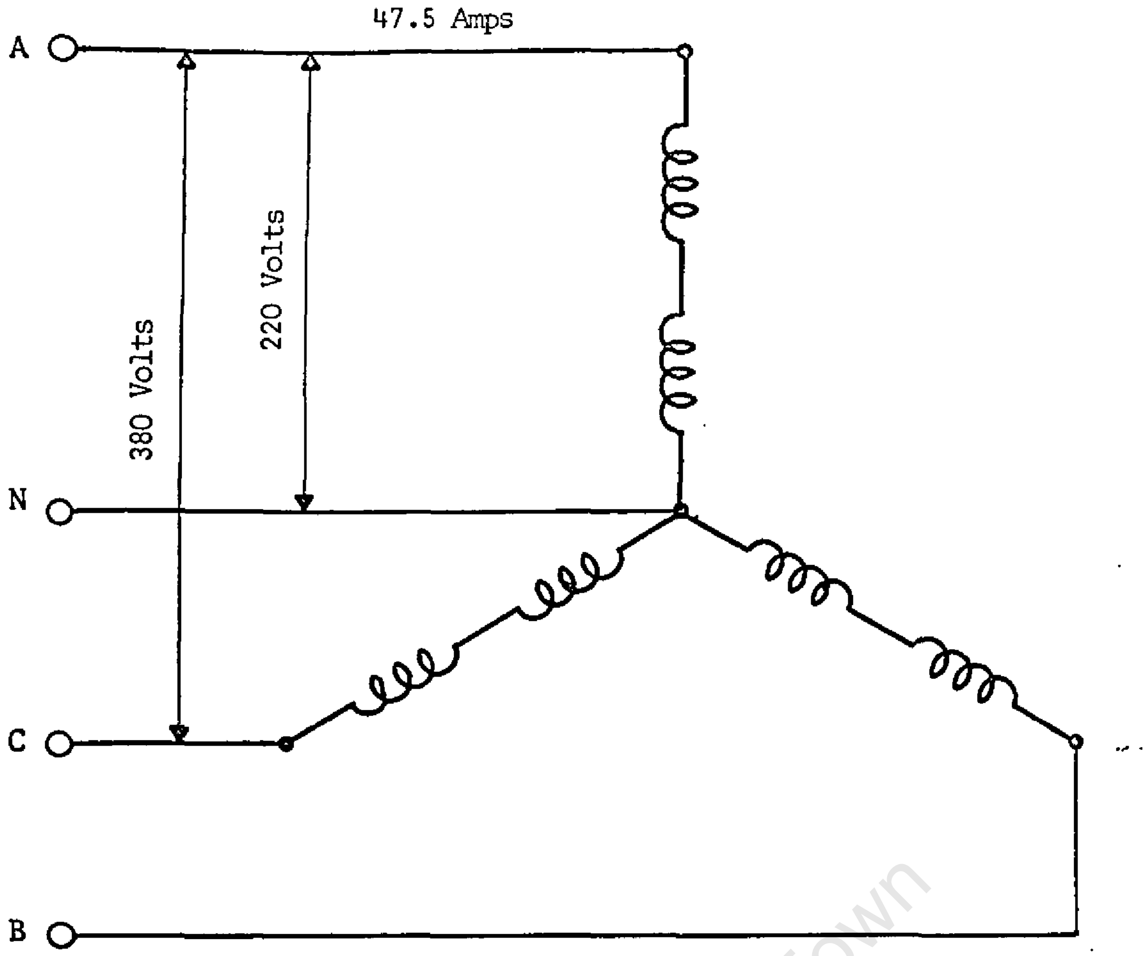
2.2 THREE-PHASE POWER OPERATION

The actual machine used for the research is the 'Markon' Type SM (and later Type B) Brushless Alternator, frame size SM39B (and later B350C) giving a 3-phase, 50 Hz output of 31.25 KVA.

For 380 to 400 volts (line) operation, the stator windings are connected in series-star as illustrated in Fig. 2.1. With an output voltage of 380 volts, the line current is:

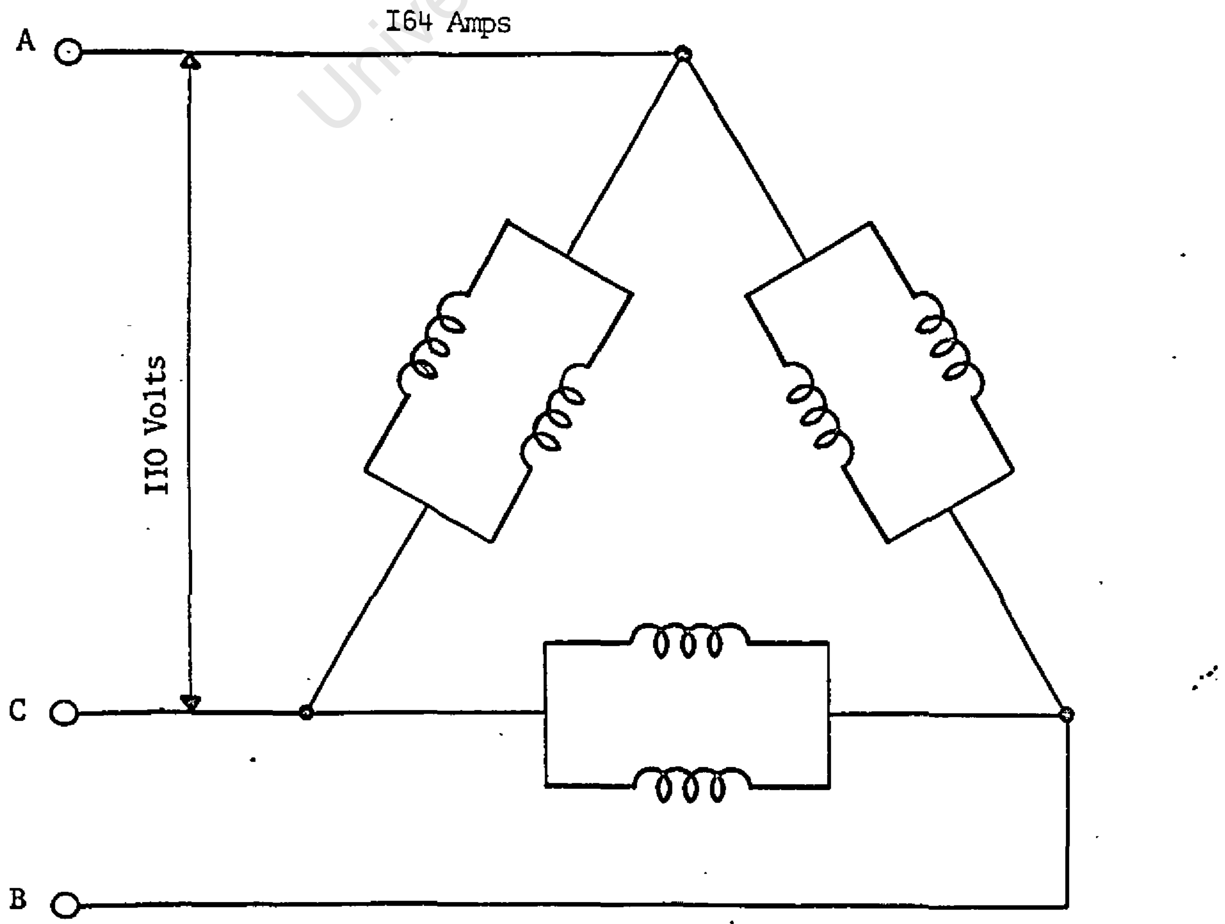
$$I = \frac{31.25}{\sqrt{3} \times 380} \times 10^3$$

$$= 47.5 \text{ amps.}$$



Series-Star Winding

Figure 2.I Stator connections.



Parallel-Delta Winding

The output voltage is controlled by means of a solid state voltage regulator unit which relies on the remanent magnetism of the machine for self excitation. To keep the voltage regulation to within $\pm$ $2\frac{1}{2}\%$ for steady state loads, the voltage across one stator winding is monitored by the regulator unit and compared with a preset reference circuit, which regulates the current flowing to the exciter field by triggering a thyristor at the desired frequency. This regulator unit comes complete with the alternator and does not require further discussion in this thesis.

2.3 D.C. WELDING OPERATION

The basic requirements for the D.C. welding generator are two independent controls giving a stepless variable current control from 40 to 400 amps and a stepless variable voltage control over the range 45 to 80 volts open circuit. This range of open circuit voltage is sufficient for most types of welding electrodes and applications.

As the required output voltage is less than 100 volts and the output current of the alternator is up to a maximum of 400 amps, the stator windings have to be reconnected in parallel-delta as illustrated in Fig. 2.1. A separate excitation circuit for operation as a D.C. welder is also necessary and should be easily switched into the exciter field in place of the voltage control unit for the A.C. supply.

The rating of the alternator remains unchanged at 31.25 KVA output at 50 Hz. For a nominal output voltage of 110 volts line, the current is:

$$I = \frac{31.25}{\sqrt{3} \times 110} \times 10^3$$

$$= 164 \text{ amps.}$$

This is a factor $2\sqrt{3}$ up on the line current for A.C. power output, being the conversion factor from series-star to parallel-delta connection.

The above ratings are for a rotor speed of 1500 r.p.m. The current ratings can be increased slightly if the speed is increased to 1800 r.p.m. giving better cooling. As the temperature rise is dependant on the square of the current the approximate increase would be -

$$\text{New } I_1^2 = 164^2 \times \frac{1800}{1500}$$

$$\text{i.e. } I_1 = 180 \text{ amps.}$$

The A.C. output is rectified through a three-phase bridge rectifier to give the necessary D.C. at the output terminals of the welder.

The theoretical current conversion factor for this type of rectifier is:

$$I\ D.C. = \frac{I_1}{.816} = 220 \text{ amps.}$$

This represents the maximum continuous current, at 100% duty cycle, obtainable from the generator.

At lower duty cycles this value can be increased to:

$$I\ D.C. = 285 \text{ amps at } 60\% \text{ duty cycle}$$

$$\text{and } I\ D.C. = 400 \text{ amps at } 30\% \text{ duty cycle}$$

The continuous rating, determined by current carrying capacity, is then:

220 amps at 32 volts

which is a suitable rating for medium sized welders.

Typical welding characteristics for a 300 amp single operator D.C. Welder are given in Figs. 2.2, 2.3 and 2.4 and will serve as a suitable comparison for the characteristics obtained from this welder.[2]

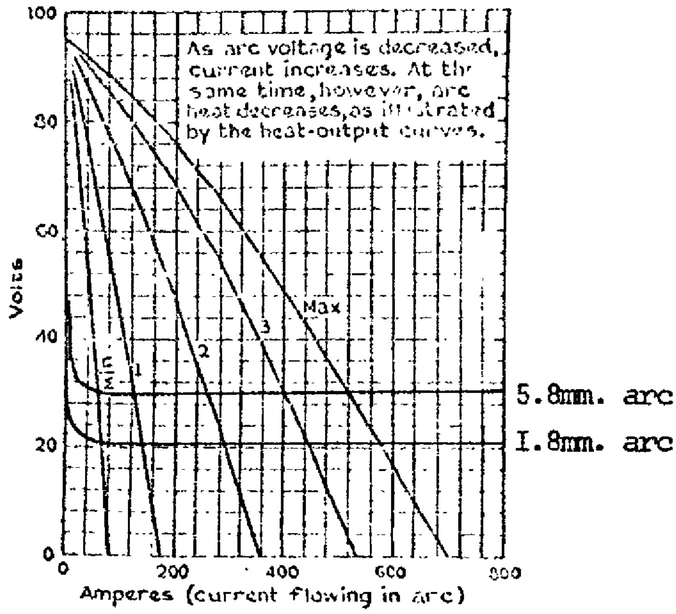


Fig. 2.2 Typical Volt-ampere Curves of a D.C. Welder.

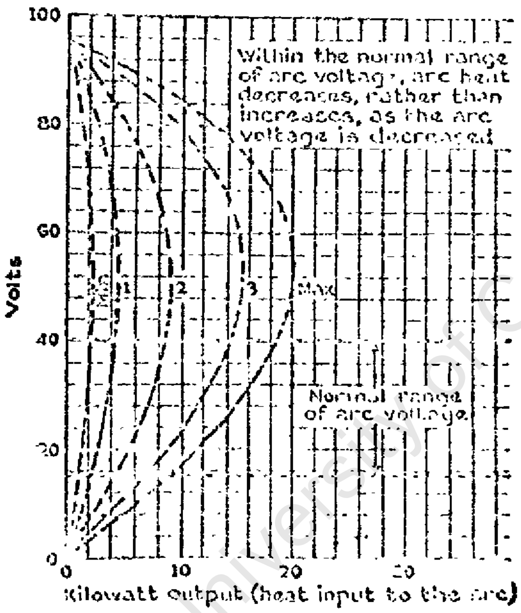


Fig. 2.3 Typical Heat-output Curves of a D.C. Welder.

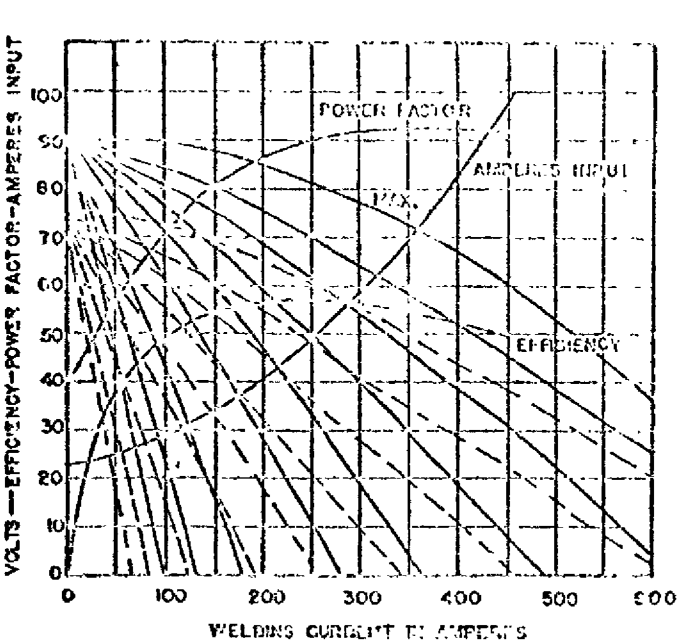


Fig. 2.4 Typical Characteristic Curves of a D.C. Welder.

3. CHARACTERISTICS OF THE MACHINE

The tests to determine the machine's characteristics consist of the usual indirect tests performed to calculate the constants of an alternator. They consist of:

(a) Open Circuit Characteristic;

(b) Short Circuit Characteristic;

(c) Zero Power Factor Load Characteristic.

As the reactors available in the laboratory for the third test have a low current rating of 32 amps at 125 volts it is necessary to have the machine connected in series-star giving the lowest current output and highest voltage.

Owing to the different pulley sizes of the V belt drive between the induction motor and test alternator, a speed of approximately 1760 r.p.m. is obtained at the alternator shaft. This corresponds to a 60 Hz output of 37.5 KVA for the machine.

For A.C. Power Output = 37.5 KVA and Output Voltage = 450 volts line, the current rating is unchanged:

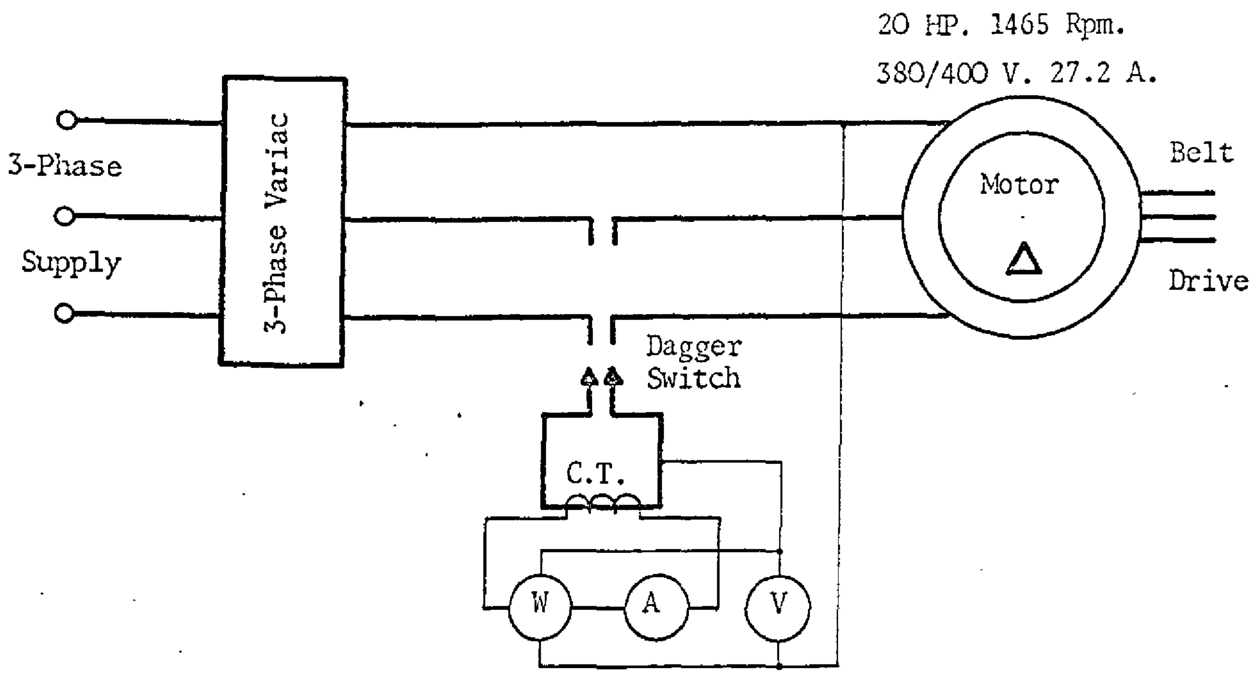
$$I = \frac{37.5}{\sqrt{3} \times 450} \times 10^3$$

$$= 47.5 \text{ amps}$$

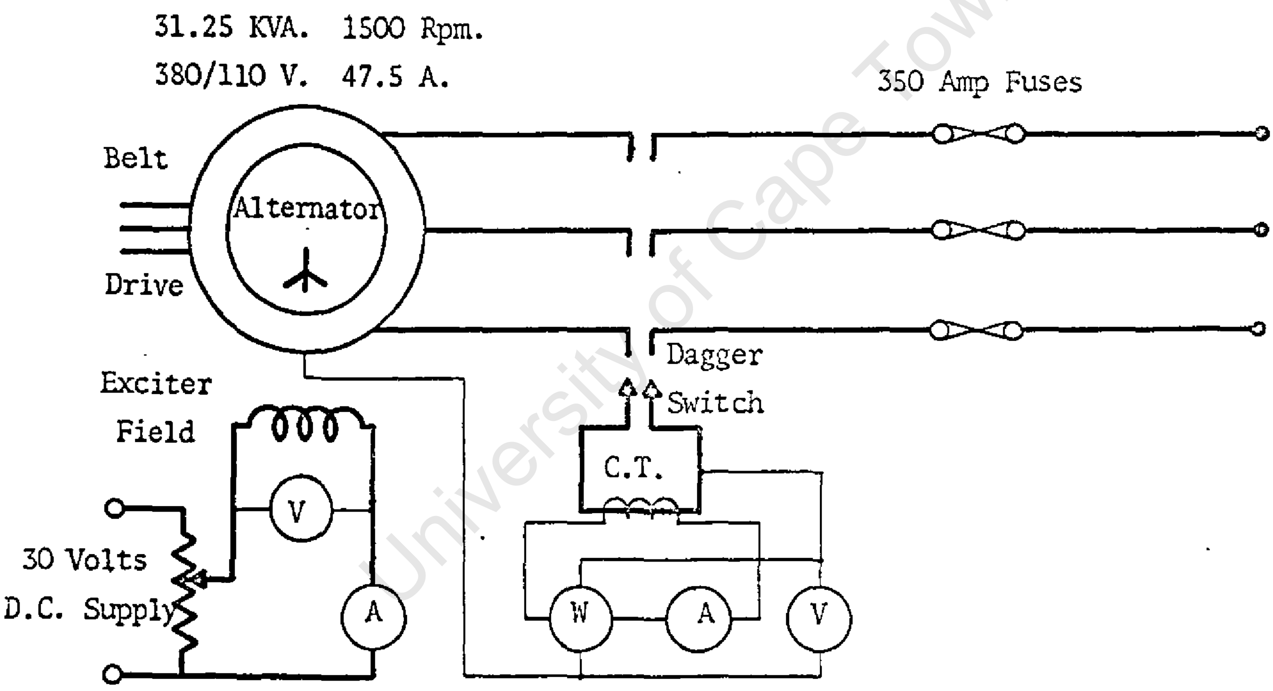
If the reactors are delta connected the current will decrease by the factor $\sqrt{3}$ to 27.5 amps, which is within their rating of 32 amps.

3.1 TESTS WITH SERIES-STAR CONNECTION

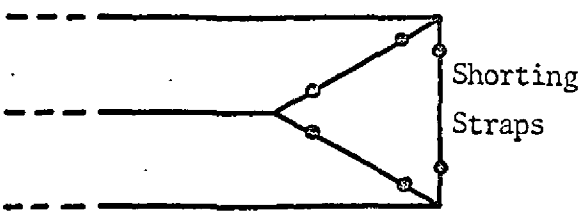
The drive motor used for all tests is an A.E.I. 20 H.P., 3-phase, 1495 r.p.m., Squirrel Cage Induction Motor. A 3-phase variac is used to run the motor up to speed and then it is switched directly onto the supply. A circuit diagram is given in Fig. 3.1.



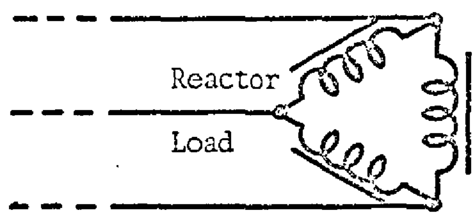
<u>Fig. 3.1</u> Circuit Diagram of Induction Motor Drive.



<u>Fig. 3.2</u> Circuit Diagram of Alternator Supply for Open Circuit Test.



<u>Fig. 3.3</u> Addition for Short Circuit Test.



<u>Fig. 3.4</u> Addition for Zero Power Factor Test.

3.1.1 OPEN CIRCUIT CHARACTERISTIC

The circuit diagram is given in Fig. 3.2 and the results obtained are shown in the O.C.C. curve of Fig.3.5.

3.1.2 SHORT CIRCUIT CHARACTERISTIC

The circuit diagram is given in Fig. 3.3. To obtain a symmetrical short circuit of the alternator, short copper straps of equal length are connected in delta across the output terminals. The results are shown in the S.C.C. curve of Fig. 3.5.

3.1.3 ZERO POWER FACTOR LOAD CHARACTERISTIC

The circuit diagram is given in Fig. 3.4. For the first part of the test the field excitation is kept constant at the value giving rated voltage at no load, while the air gaps of the reactors are increased in steps, keeping the line currents balanced.

The second part of the test is the Full Load Current Characteristic and this is obtained by reducing the reactor air gaps gradually and adjusting the field excitation each time for full load current in each line of the alternator.

The Synchronous Impedance, Zs ohms per phase is calculated from the Open and Short Circuit Characteristics where:

$$Z_s = \frac{E_o}{I_{sc}}$$

and the results are shown in the Zs curve of Fig. 3.5.

Curves of the Open circuit and Zero Power Factor current characteristics are given in Fig. 3.6 and show the construction of the Potier triangle to determine the constants of the machine.

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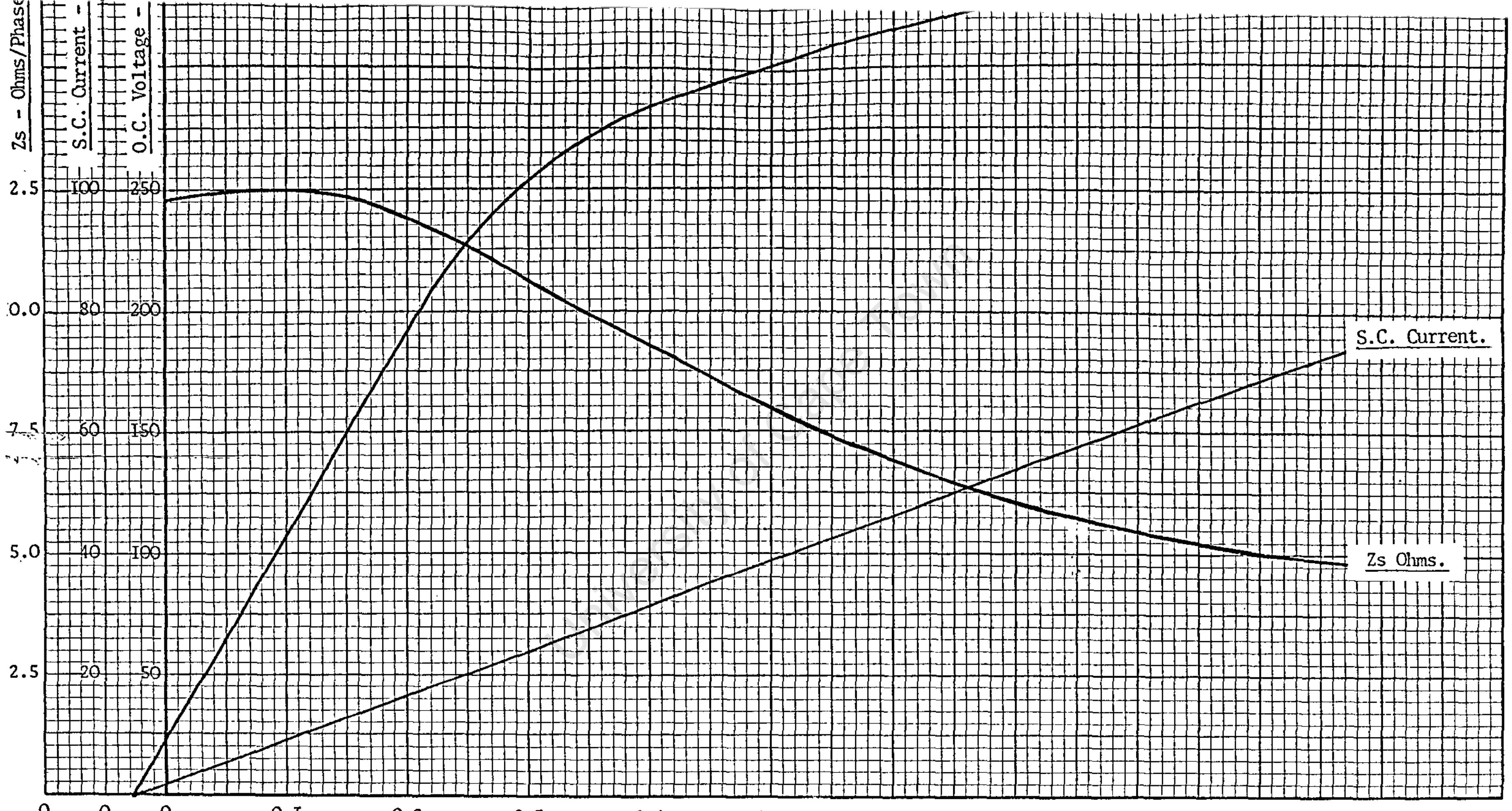


Fig. 3.5 Open, Short Circuit & Zs Characteristics for Series-Star Connection.

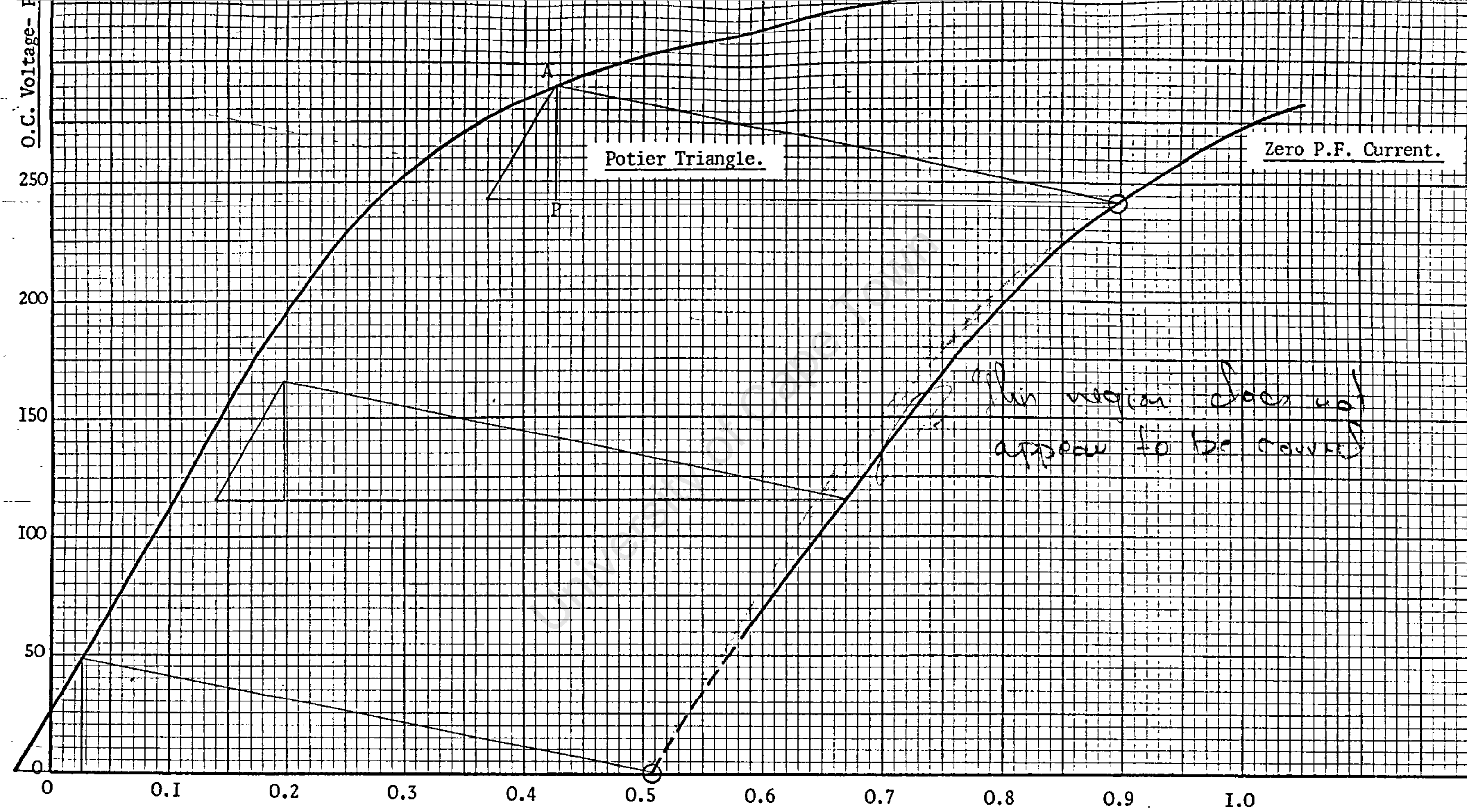


Fig. 3.6 Open Circuit & Zero P.F. Current Characteristics for Series-Star Connection

3.1.4 STEADY STATE CONSTANTS OF THE MACHINE

(a) Stator and Field resistance:

The resistance of one stator phase winding and the field winding was measured using a Wheatstone bridge and found to be:

Resistance of stator winding, R_a, = 0.20 ohms

Resistance of field winding, R_f, = 27.2 ohms

(b) Stator inductive reactance, X_L:

For the Zero Power Factor test, the constant load current = 40 amps. Taking the point on the Z.P.F.F.L.C. at 280 volts the Potier triangle is constructed. Then:

$$E_z = AP = 48 \text{ volts from the triangle}$$

$$\text{Now} \quad E_z = I_{FL}\sqrt{X_L^2 + R_a^2}$$
$$\text{i.e.} \quad 48 = 40\sqrt{X_L^2 + 0.2^2}$$
$$\therefore \quad X_L^2 = 1.2^2 - 0.2^2$$
$$= 1.4$$

$$\therefore \quad X_L = 1.18 \text{ ohms per phase}$$

(c) Synchronous Impedance of machine, Z_s:

This is determined from the open and short circuit characteristics, as before:

$$Z_s = \frac{E_o}{I_{sc}}$$

It may also be found by dividing the difference between the open circuit and zero power factor characteristics by the constant full load current of the test for all values of field excitation.

(d) Equivalent Circuit of the Machine:

The equivalent circuit and corresponding vector diagram of the alternator are given in Fig. 3.7.

3.2/...

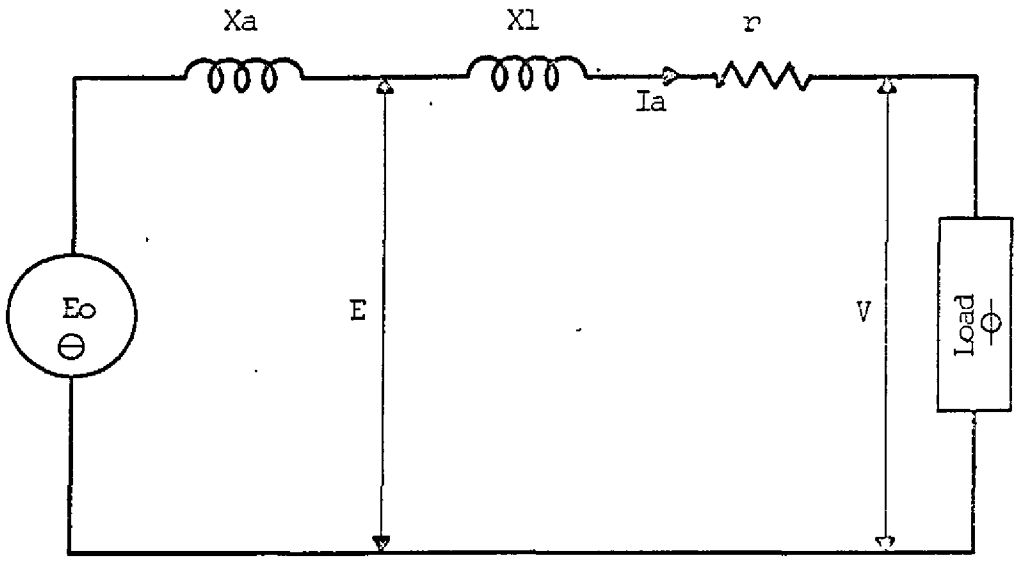
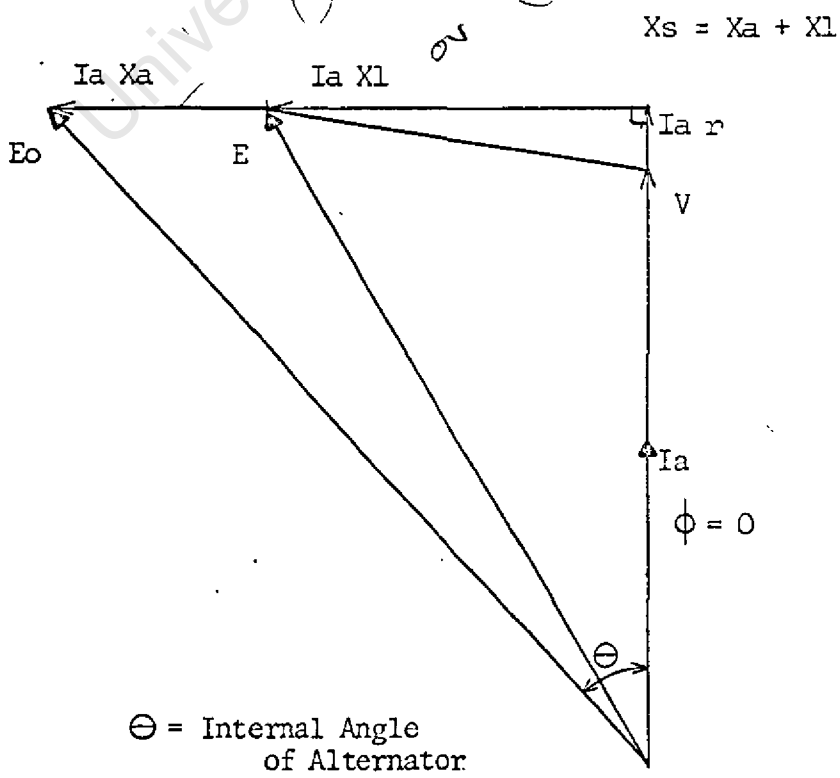


Fig. 3.7 Equivalent Circuit of Alternator.

Based on which or Each?



Vector Diagram for Equivalent Circuit.

(with Unity Power Factor Load)

3.2 TESTS WITH PARALLEL-DELTA CONNECTION

In order to check the constants of the machine when connected in parallel-delta for welding, the tests carried out in section 3.1 were briefly repeated.

3.2.1 OPEN CIRCUIT CHARACTERISTIC

The results obtained are shown in the O.C.C. curve of Fig. 3.8.

3.2.2 SHORT CIRCUIT CHARACTERISTIC

The results obtained are shown in the S.C.C. curve of Fig. 3.8.

3.2.3. ZERO POWER FACTOR TEST

As the reactors have a low current rating it was not possible to perform a full load test, but instead a few readings were taken at a reduced current.

Curves of the open and short circuit characteristics, together with the corresponding Zs characteristic are given in Fig. 3.8. The Potier triangle for a point on the zero power factor curve is also given.

3.2.4 STEADY STATE CONSTANTS OF THE MACHINE

(a) Stator resistance, Ra.

In this case the stator windings consist of two parallel coils in delta connection, so the phase resistance decreases by a factor of 12 from series-star.

Stator Resistance, Ra = .02 ohms per phase.

(b) Stator inductive reactance, XL.

For the zero power factor test the load current was 60 amps. Taking the point at 140 volts the Potier triangle is constructed. Then:

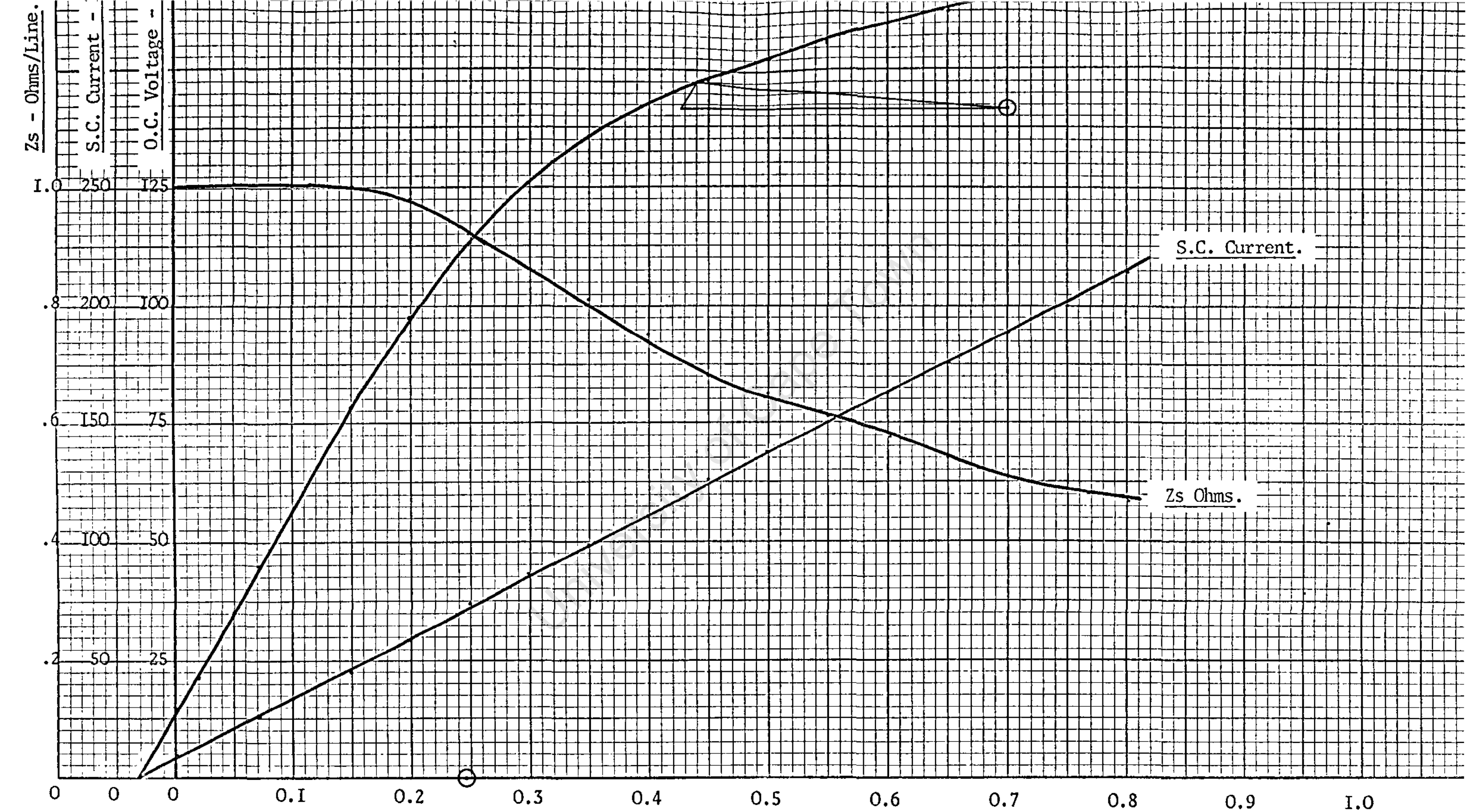


Fig. 3.8 Open, Short Circuit & Zs Characteristics for Parallel-Delta Connection.

$$E_z = AP = 6 \text{ volts from the triangle}$$

$$E_z = I_L\sqrt{X_L^2 + R_a^2}$$

$$\text{i.e. } 6 = 60\sqrt{X_L^2 + .02^2}$$

$$X_L^2 = .1^2 - .02^2$$

$$= .0096$$

$$\therefore X_L = .098 \text{ ohms per phase}$$

This agrees with the previous value of 1.18 ohms per phase when divided by the conversion factor of 12 for a series-star to parallel-delta connection.

(c) Synchronous Impedance, Z_s.

This is determined from the open and short circuit characteristics as before:

$$Z_s = \frac{E_o}{I_{sc}}$$

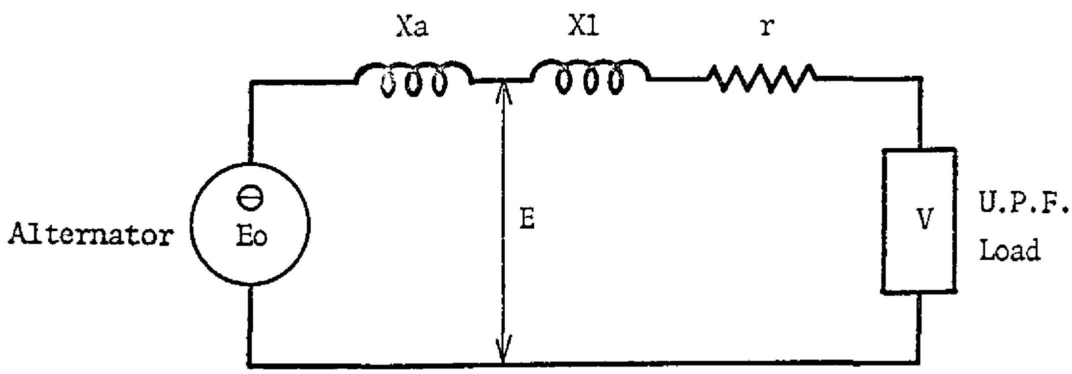
The values obtained from this test agree well with the previous test taking the conversion factor of 12 into account.

3.3 CONSTANT EXCITATION CHARACTERISTICS

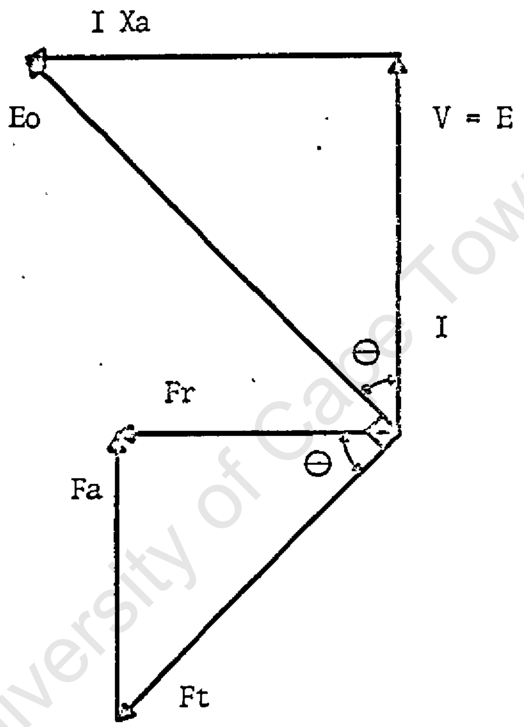
A good indication of the machine's load characteristics at constant excitation can now be obtained using the information gained in the previous tests. It can be assumed that the D.C. welding arc resembles a unity power factor load incorporating the 3-phase diode bridge rectifier. This will be confirmed later in the load test results.

A graphical method can be used to deduce the required characteristics by using the voltage vector diagram in conjunction with the m.m.f. vector diagram and the open and short circuit characteristics. In this case the quantities X_L and r are neglected and Z_s alone is used in the equivalent circuit. This is illustrated in Fig. 3.9.

The/...



Equivalent Circuit of Alternator.



Vector Diagram (neglecting X1 & r. ie. V = E)

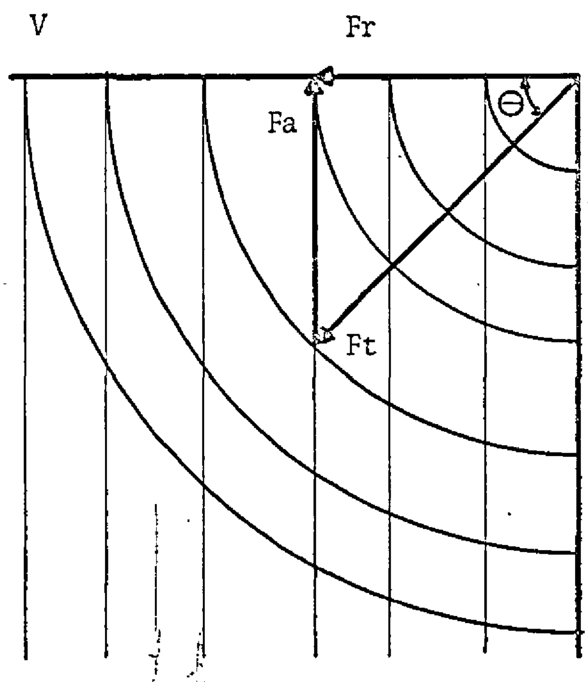


Fig. 3.9 Derivation of Constant Excitation Characteristics.

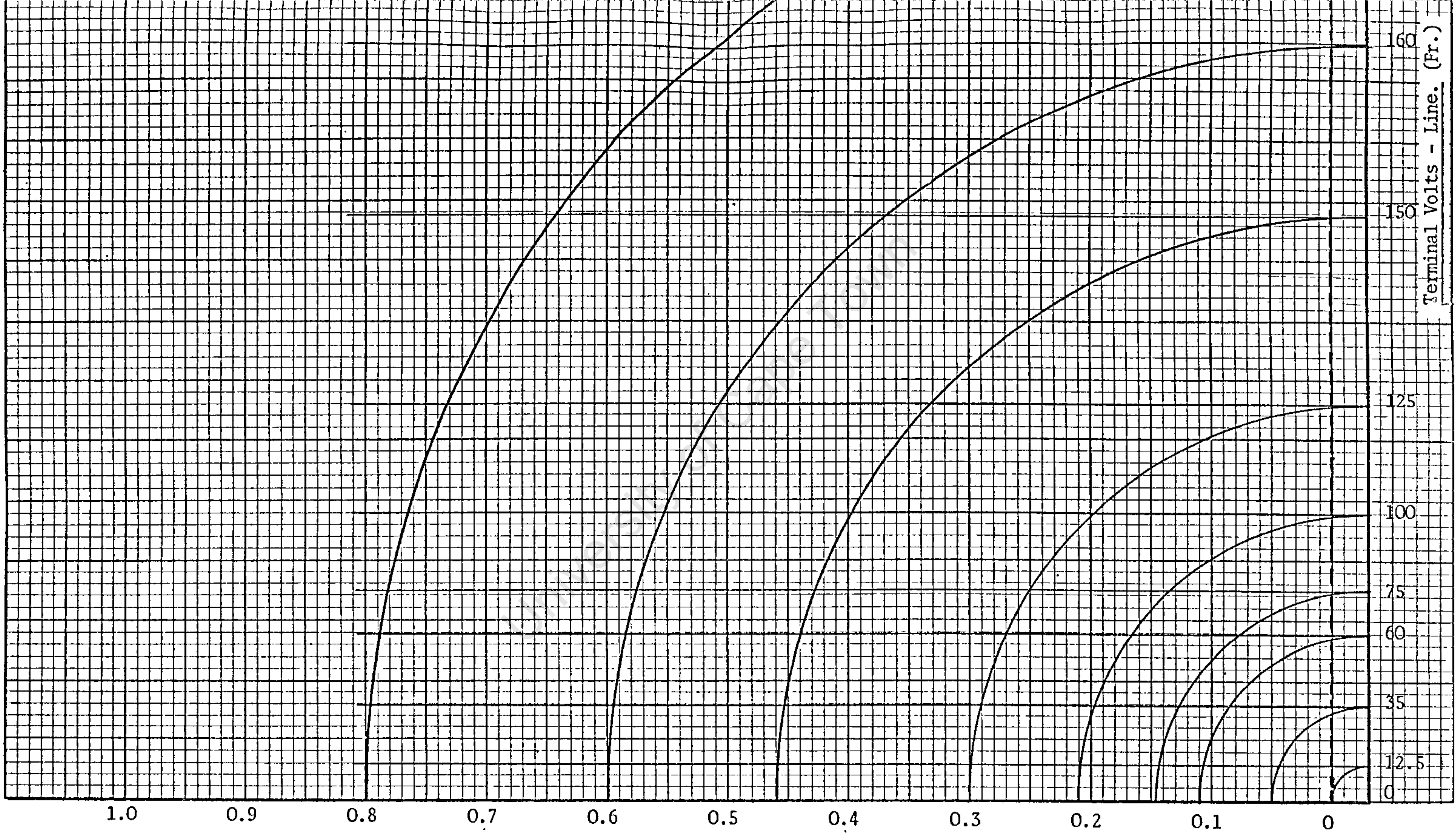


Fig. 3.10 Construction for Constant Excitation Characteristics.

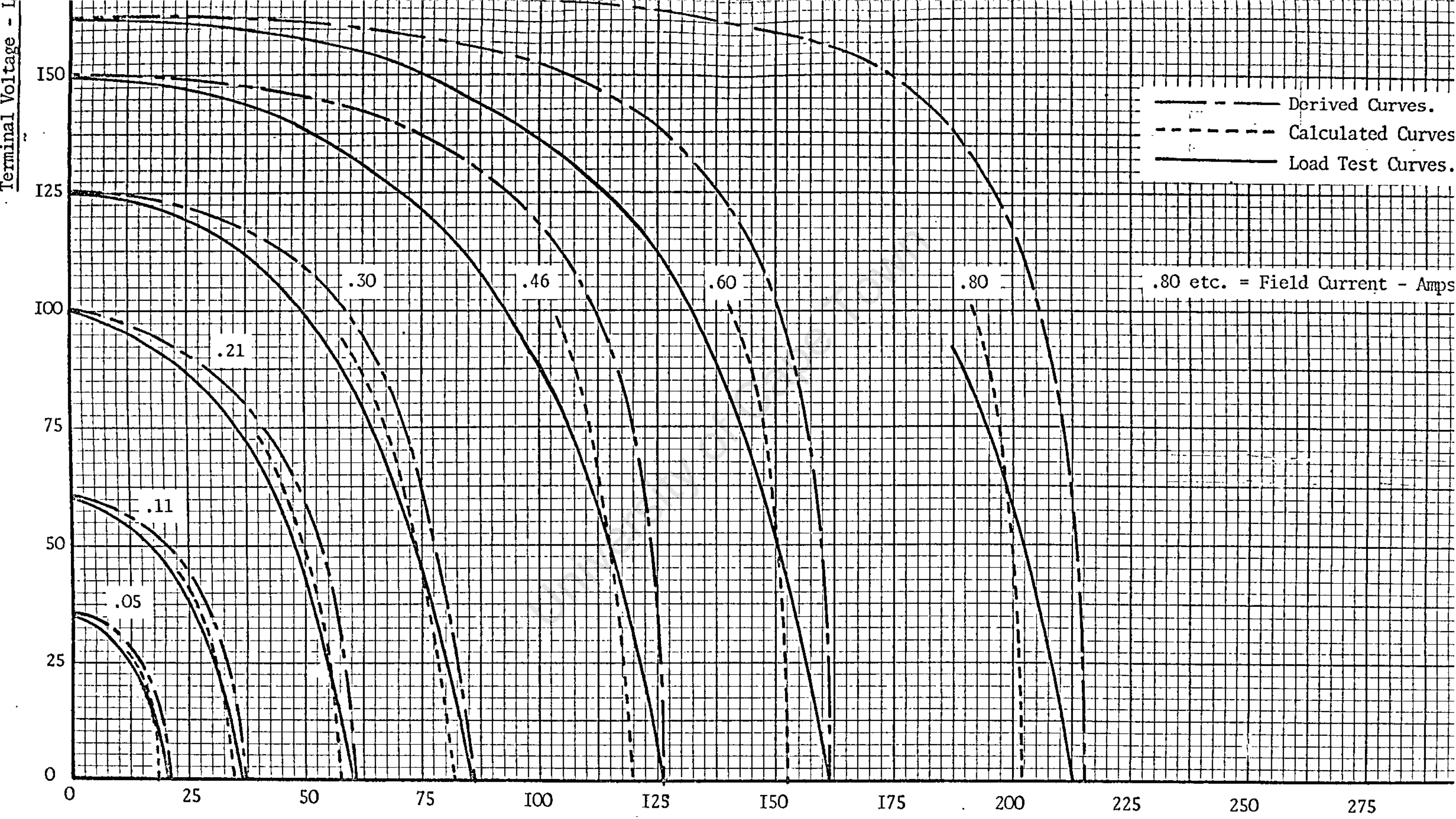


Fig. 3.11 Constant Excitation Characteristics with Unity P.F. Load.

The quantity Ft is represented by circular arcs equivalent to the open circuit voltage Eo for various field currents equivalent to Fa. Then for various terminal voltages V, represented by parallel lines Fr, the values of load current I can be deduced from the short circuit characteristic for the same excitation Fa. The construction for these constant excitation characteristics is given in Fig. 3.10 and the values obtained are in Table 3.1 in Appendix 1. The curves are given in Fig. 3.11, together with the results obtained from the actual load test with a unity power factor load.

It is possible to take into account the effect of XL on the characteristics as the m.m.f.'s in the machine are linear functions of the voltage and current when the machine is unsaturated. For voltages less than 100 volts open circuit, the following equation can be used to find the current through a unity power factor load at constant excitation:

$$I = \frac{\sqrt{(Ft + .03)^2 - 5.5 \times 10^{-6} \times V^2}}{4.12 \times 10^{-3}} \text{ amps}$$

where V = voltage across load.

Ft = excitation field current.

The derivation of this equation appears in Appendix 2 and the computer print out of results are given in Table 3.2 in Appendix 1. Those results are also plotted together with the previous results in Fig. 3.11 for comparison.

4. BASIC PRINCIPLES OF CONTROL CIRCUIT

POSSIBLE METHODS OF CONTROL

Various methods of controlling field excitation were considered here and in previous work on the subject.[3] These are as follows:

(a) SELF-EXCITATION CIRCUITS

Circuits using the machine's remanent magnetism to obtain open circuit volts would seem the most suitable and simplest method. This is possible but when the arc is momentarily shorted the feedback voltage falls immediately to zero and so the field excitation is interrupted and the voltage recovery is too slow to maintain a stable arc. Other circuit components would be required to control the excitation when welding. These may include current transformers, rectifiers and magnetic amplifiers to boost the field current when the welding current is increased on shorting the arc and also when using heavy electrodes.

Relying on self excitation for the welding machine is thus impractical and the need for a stable source of reference voltage is essential for this purpose.

(b) CIRCUITS WITH REFERENCE VOLTAGES

It is possible to control the open circuit voltage of the machine precisely when using a stable reference supply. Also, when the arc is shorted, the field excitation will not suddenly fall to zero but be determined by the supply voltage to the field. The arc voltage recovery will thus be rapid after a short, which is an important pre-requisite for arc stability.

To achieve current control when welding it is necessary to have some form of feedback from the output side so

that/...

that the field excitation can be increased when the machine is on load.

A simple circuit network which will provide increased excitation on load is given in Fig. 4.1.

This is a common T type two-port network with two active elements, the reference and output voltages and three passive resistance elements. Knowing some of the values of the elements, the complete network may be solved by the usual circuit equations.

From the figure we have:

$$VR = (If + Io)RC + If(RA + Rf) \qquad \text{..........(1)}$$

$$VO = (If + Io)RC + Io\ RB \qquad \text{..........(2)}$$

$$\therefore\ VR - VO = If(RA + Rf) - Io\ RB \qquad \text{..........(3)}$$

From the O.C. characteristics we know:

For VO = 60 volts D.C., If = 0.08 amps and Rf = 27 Ω

From the S.C. characteristics we know:

For Io = 150 amps D.C., If = 0.45 amps.

$\therefore$ For O.C. conditions

$$VR - 60 = .08\ (RA + 27) - Io\ RB$$

and for S.C. conditions

$$VR = .45\ RA + 27 + \frac{RCRB}{RC + RB}$$

Assume RA = 0 Ω and VR = 30 volts D.C. and maximum Io = 1 amp

$$\text{so } 30 - 60 = .08(0 + 27) - 1 \times RB$$

$$RB = .08 \times 27 + 60 - 30$$

$$\doteq 32\ \Omega$$

Substituting in (2)

$$60 = (.08 + 1)RC + 1 \times 32$$

$$RC = \frac{28}{1.08} = 26\ \Omega$$

Check/...

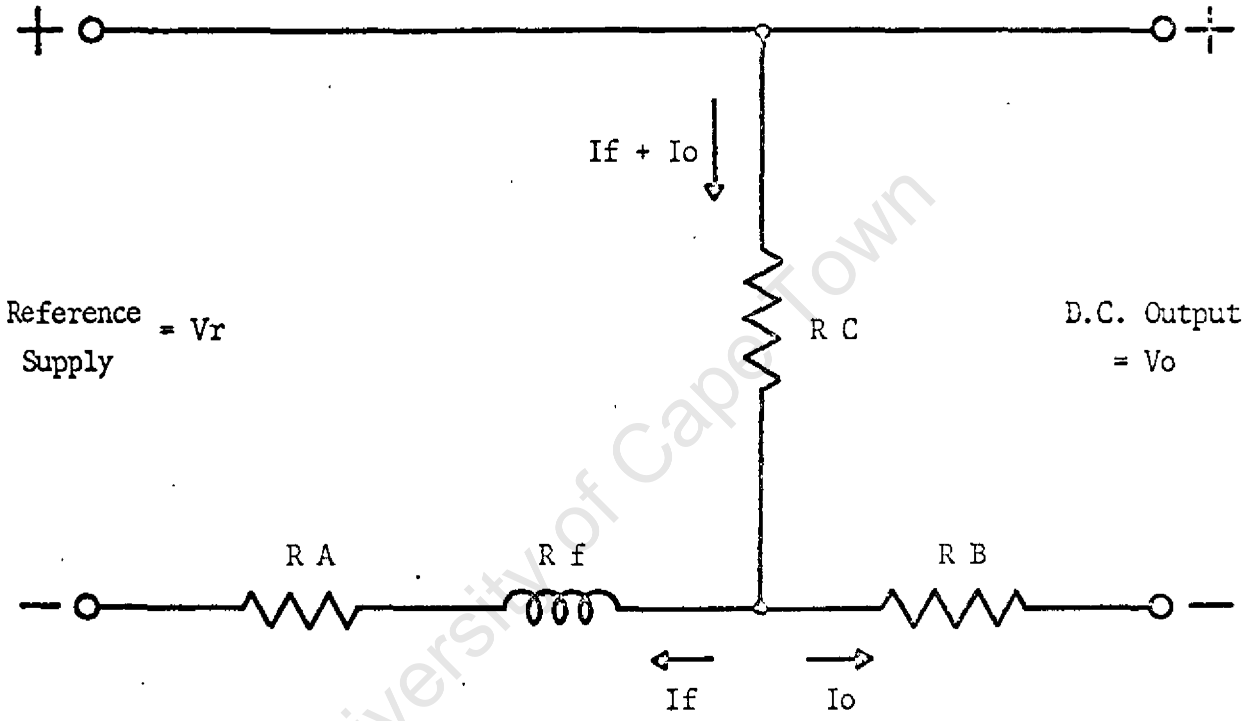


Fig. 4.1 Basic Exciter Field Control Circuit.

Check for S.C. conditions

$$30 = If\left(0 + 27 + \frac{26 \times 32}{26 + 32}\right)$$

$$If = \frac{30}{27 + 14} \doteqdot .72 \text{ amps}$$

This is too high for approx. .45 amps required, so recalculate for If = .45 amps to find RA.

$$RA + 27 + \frac{26 \times 32}{26 + 32} = \frac{30}{.45} = 66$$

$$\therefore RA = 66 - 41 = 25\ \Omega$$

Recalculating for O.C. conditions:

$$RB = .08(25 + 27) + 60 - 30$$

$$= 4.1 + 60 - 30$$

$$\doteqdot 34\ \Omega$$

Substituting in (2)

$$60 = (.08 + 1)RC \times 1 \times 34$$

$$RC = \frac{26}{1.08} \doteqdot 24\ \Omega$$

Check for S.C. conditions now

$$30 = If\left(25 + 27 + \frac{24 \times 34}{24 + 34}\right)$$

$\therefore If = \frac{30}{66} \doteqdot .45$ amps; this checks.

Check for welding conditions at 150 amps

Say 150 amps output at VO = 25 volts D.C. arc voltage

From equation (3)

$$VR - VO = If^1(RA + Rf) - Io^1\ RB$$

For If^1 = .45 amps as before

$$Io^1 = \frac{.45(25 + 27) - 30 + 25}{34}$$

$$= .53 \text{ amps.}$$

This is less than the assumed maximum of 1 amp so the circuit should operate satisfactorily.

From the previous calculations it is apparent that the

short/...

short circuit current is largely dependant on the value of RA while the open circuit voltage is governed mainly by the values of RB and RC. This circuit employs negative voltage feedback from the D.C. output in order to control open circuit conditions and relies on a high reference voltage to give increased field excitation for normal welding conditions. Other methods of increasing field excitation when welding are considered in a later section.

The circuit was tried on the machine and performed as expected from the preliminary calculations. The values of RA, RB and RC were adjusted slightly to give optimum output conditions and various load test were carried out to determine the machine's performance as a welder.

5. INITIAL LOAD CHARACTERISTICS

A unity power factor, low resistance, load bank is used to provide a steady artificial D.C. arc load for these tests. It will thus be possible to compare these test results with the theoretical constant excitation curves determined in Section 3.

5.1 CONSTANT EXCITATION CHARACTERISTICS - NO VOLTAGE FEEDBACK

The circuit diagram of the load circuit is given in Fig. 5.1. The values of the field currents used are the same as those taken for deriving the theoretical constant excitation curves to facilitate easy comparison between results. The load test results are given in Table 5.1. Curves of these results are plotted in Fig. 3.11 together with the curves of the derived constant excitation characteristics.

There is generally close agreement between curves for the same field current using the m.m.f. formula which takes into account the XL of the machine, but at higher values of field current the curves derived from the graphical method, using Zs, deviate from the actual load curves thus indicating the error introduced by neglecting r for this method.

The lower values of Zs in the saturated region at increased field currents also give values of line current greater than actually obtained for the load test. However the saturation of the machine is not the only factor which influences the high line currents. The distorted output voltage waveform of the alternator on a rectifier load may affect the m.m.f. produced in the machine at the higher currents. The voltage waveforms are given in the Recordings of a later section. Current waveforms also show a slight distortion of the peaks at increased current.

The/...

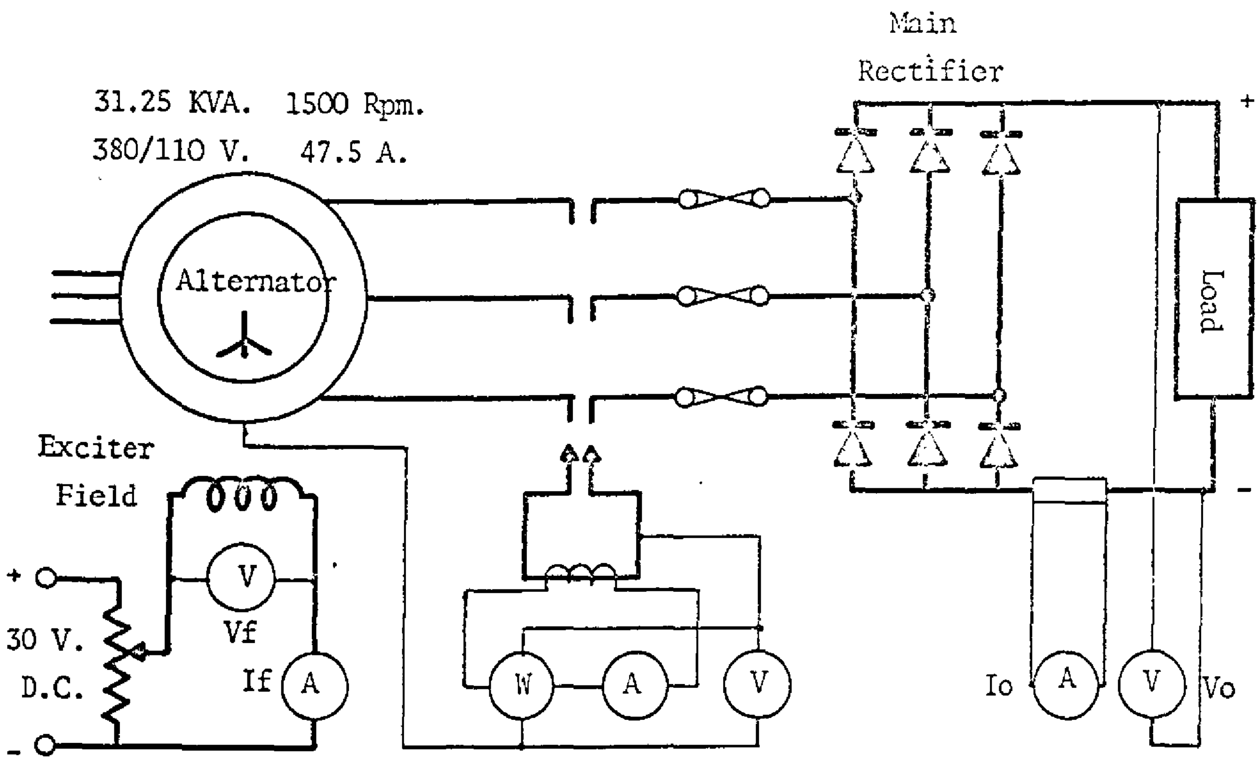


Fig. 5.1 Load Circuit Diagram with Separate Excitation.

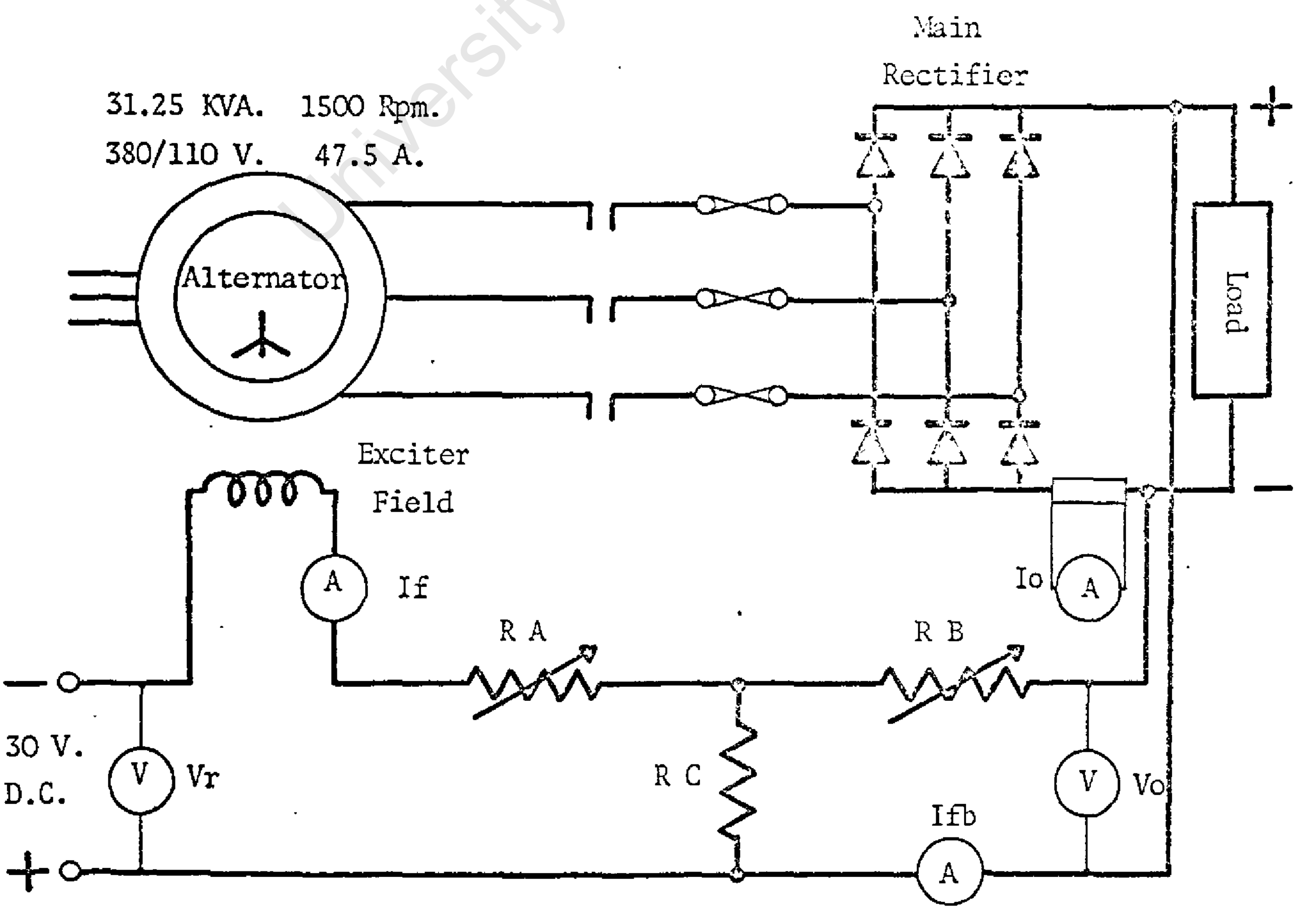


Fig. 5.2 Load Circuit Diagram with Voltage Feedback.

The load power factor may also be affected by the small inductance of the resistive load, thus reducing the voltage.

5.2 EXCITATION CHARACTERISTICS - WITH VOLTAGE FEEDBACK

The excitation circuit used for this test is the one designed in Section 4 using negative voltage feedback and is given in Fig. 5.2. The rest of the load circuit remains as given in Fig. 5.1.

The value of resistor RA is adjusted to give the short circuit excitation settings used in Section 5.1 and resistors RB and RC adjusted to give a set open circuit voltage of 50 volts A.C. for one test and 70 volts A.C. for a second test. These settings are kept constant during the tests and the resistive load bank is decreased in steps to short circuit conditions. The results obtained are given in Table 5.2. and the curves in Fig. 5.3. A comparison can now be made between the load curves obtained with and without voltage feedback. As negative feedback is used to control the voltage, the system will be stable during welding operations and the load curves with feedback resemble closely the typical welding characteristics given in Fig. 2.4.

To show the effect of the negative feedback from the D.C. output on the field excitation, curves of constant O.C. voltage relating field current to feedback current are given in Fig. 5.4.

5.3 ALLOCATION OF LOSSES IN POWER SYSTEM

These tests involve measuring the power into, through and out of the complete generating system. The results then show exactly where the power is being used and where the losses are greatest.

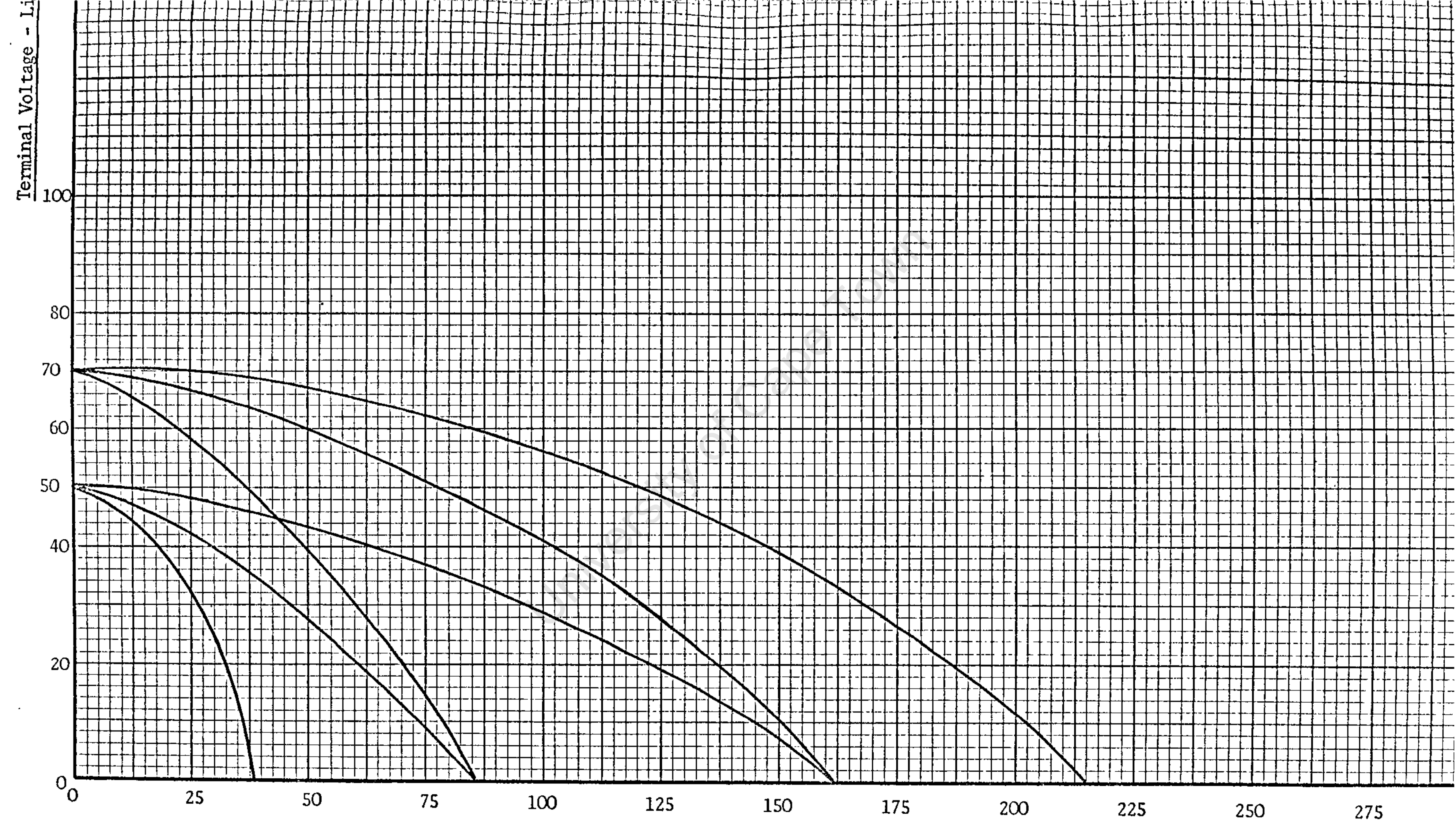


Fig. 5.3 Load Characteristics with Voltage Feedback.

The tests were taken with the machine on separate excitation as before and the circuit diagram of the complete power system is given in Fig. 5.5. The results obtained are listed in Table 5.3 and a summary of the losses and efficiencies of the system are given in Table 5.4. for various field excitations. Curves of efficiency and power factor are given in Fig. 5.6.

The relative low efficiencies of 60 - 65% obtained for the A.C. Power out of the alternator are due to the combined efficiencies of the motor and alternator and also to the losses in the V-belt drive between the machines.

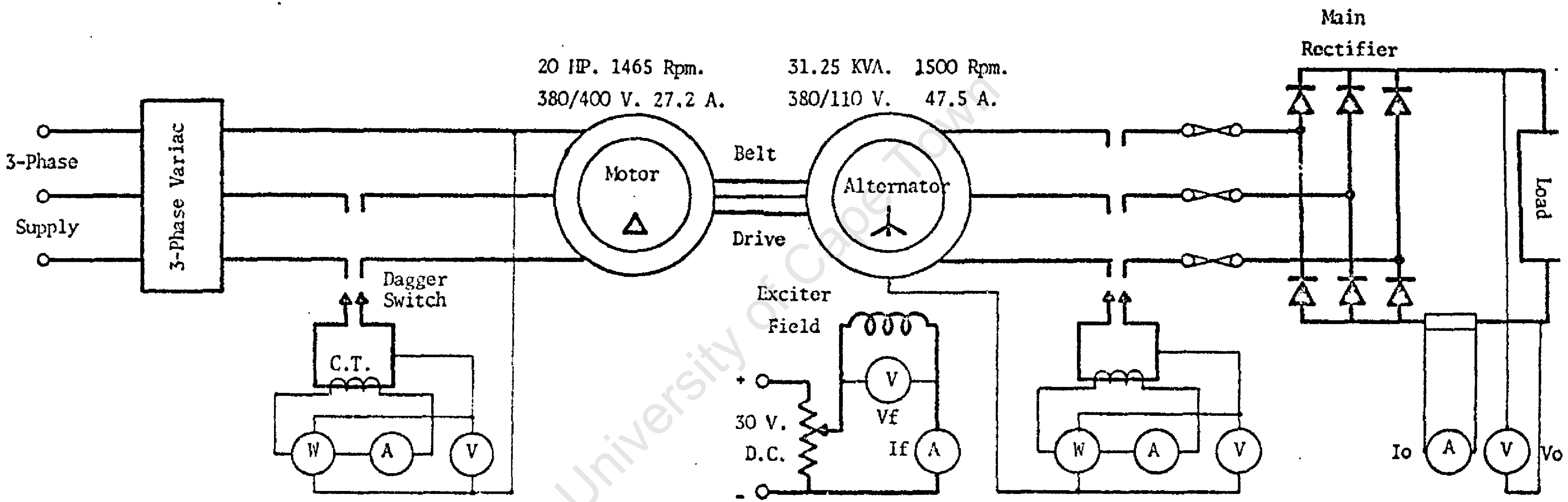


Fig. 5.5 Complete Circuit Diagram of Power System.

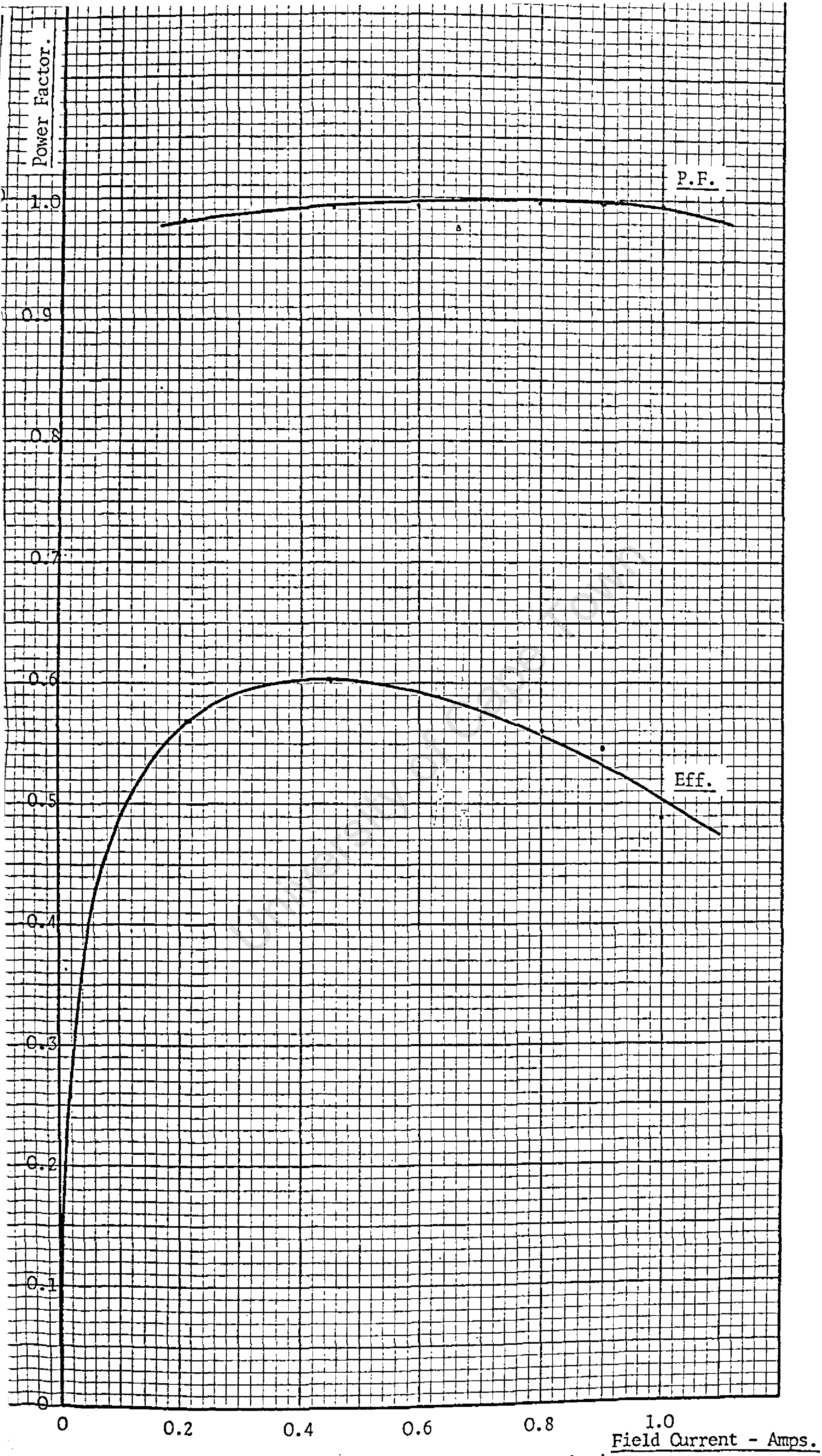


Fig. 5.6 Efficiency & Power Factor Load Characteristics.

6. INITIAL WELDING CHARACTERISTICS

6.1 TESTS WITH THE BRUSHLESS WELDER

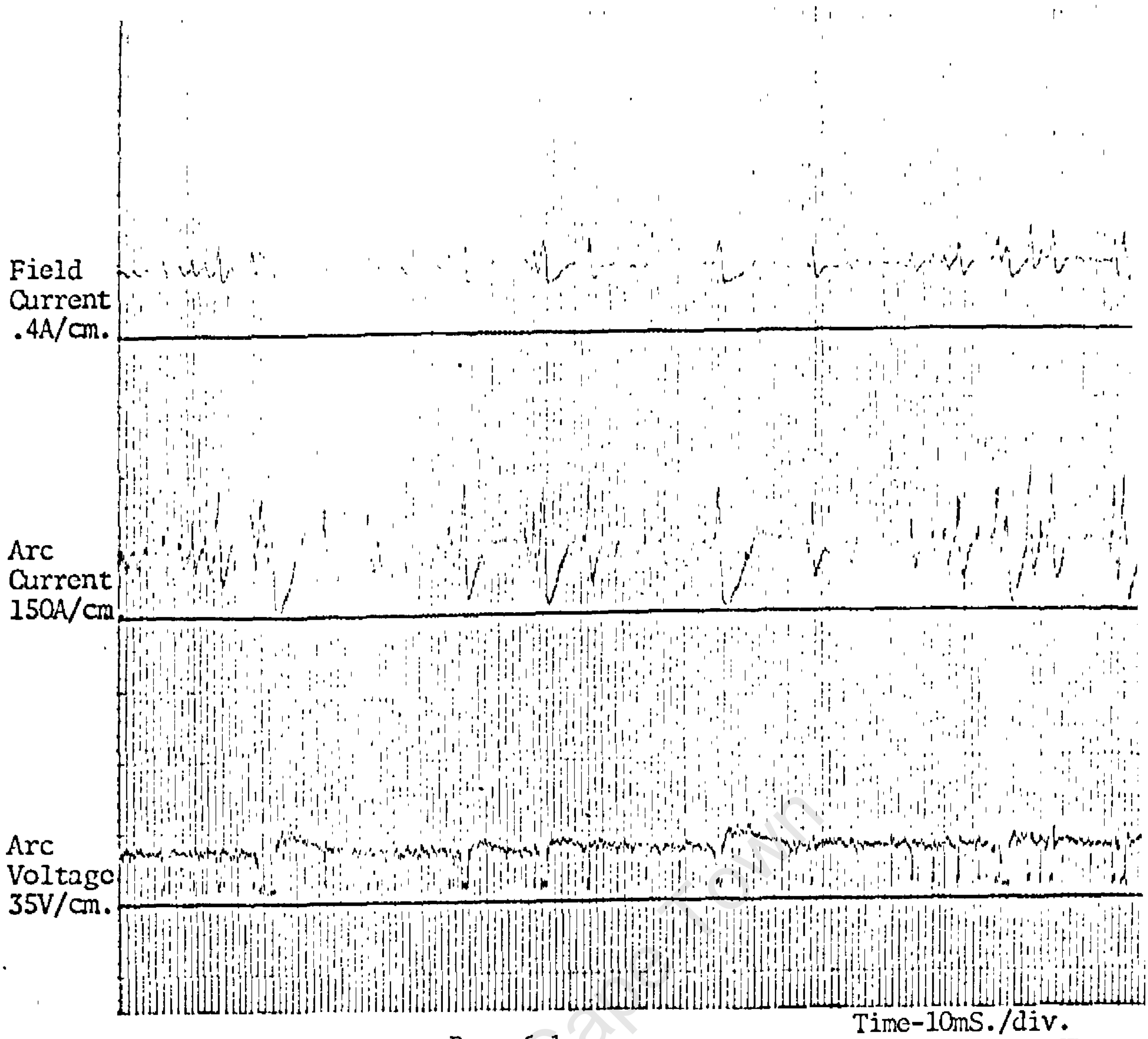
As shown in the previous section the machine's steady state characteristics are now suitable for welding. The first trial welds made with the machine were not very successful as difficulty was experienced in striking the arc and maintaining a consistent flow of metal from the rod to the work. It was found that an open circuit voltage of 60 volts D.C. made the arc striking easier but the arc had a tendency to extinguish or 'snuff out' during welding and would not restrike automatically.

Recordings of arc voltage and current and field current were made with an Ultra-Violet Chart Recorder (S.E. Laboratories) as this instrument has the response and sensitivity necessary to record the rapid changes in arc conditions when welding.

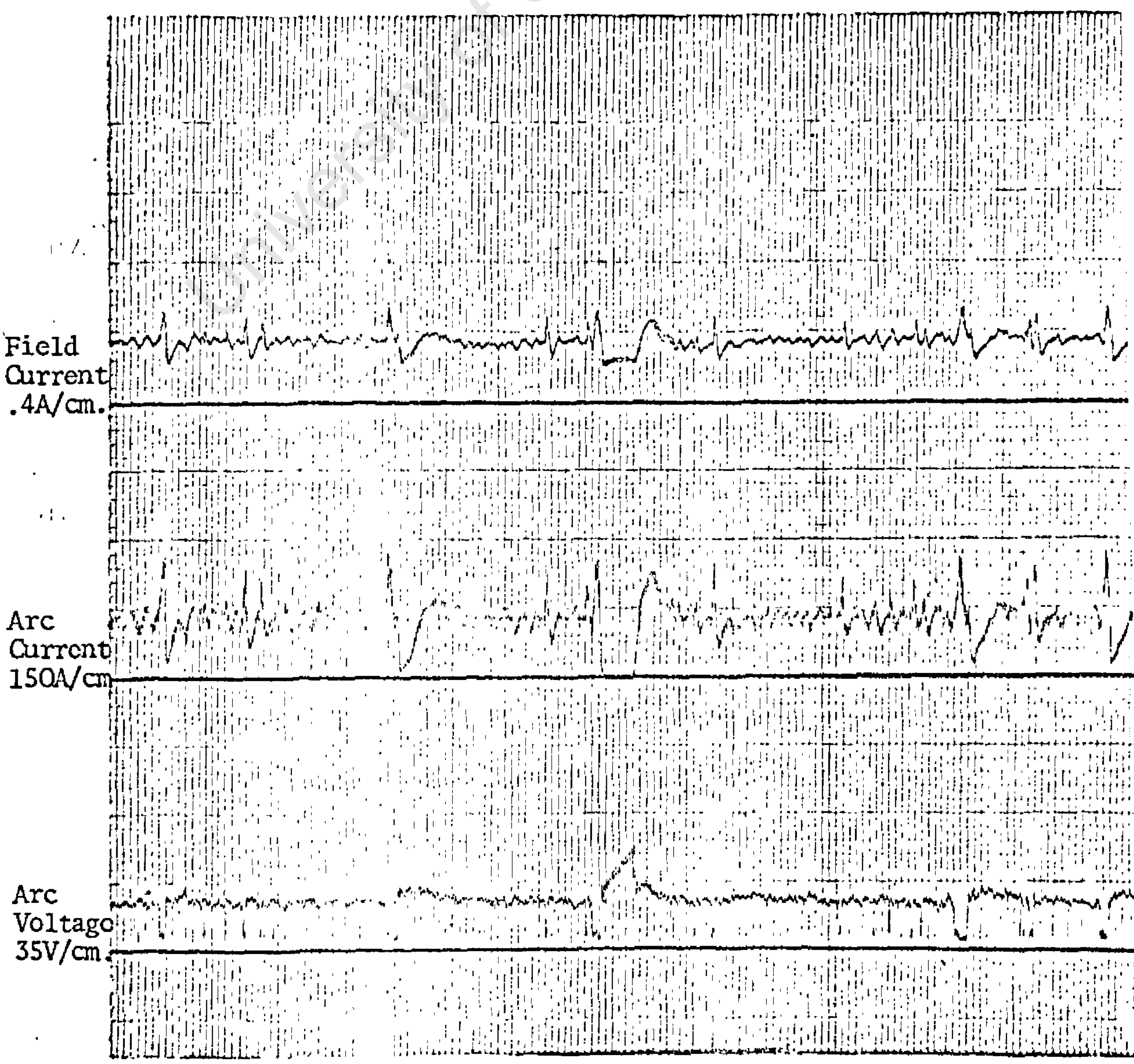
The initial welding characteristics with the basic control circuit used in Section 5.2 are given in Recordings 6.1 and 6.2. The calibration values for each trace are given at the left of the recordings and the time scale calibration at the bottom of the recordings.

(a) Rec. 6.1 illustrates the rapid changes in arc voltage which occur when the globules of molten metal short out the arc. The duration of short circuit can easily be obtained from the time scale of each recording and this can vary from about 1 to 30 milliseconds depending on the size and type of welding rod being used and also the output current setting. Corresponding to the rapid changes in

arc/...


Field
Current
.4A/cm.
Arc
Current
150A/cm
Arc
Voltage
35V/cm.
Time-10mS./div.

Rec. 6.1


Field
Current
.4A/cm.
Arc
Current
150A/cm
Arc
Voltage
35V/cm

Rec. 6.2

arc voltage are the slightly more damped changes in arc current and field current. For a sudden short of the arc voltage there is an increase in arc and field current determined by the transient characteristics of the machine at short circuit. The traces indicate almost identical waveforms for the arc and field currents with no phase difference between them. This shows that there is very tight coupling between the magnetic circuits of the alternator stator and field exciter stator windings.

The D.C. arc voltage and current waveforms have a 300 Hz ripple superimposed on the D.C. waveform. This is characteristic for 50 Hz supplies using a 3 phase full wave bridge rectifier for the D.C. output.

An important property of the current waveforms is the sudden undershoot which occurs immediately following a short circuit or zero arc voltage portion of the voltage waveform. If the current undershoot is severe and of long duration the arc will be extinguished or 'snuff out' and a loss of welding current results. This is an undesirable characteristic which makes the welder unacceptable for industrial use. Although a sharp rise in the recovery voltage after short circuit is necessary to restrike the arc automatically, if the voltage approaches the open circuit value at this instant, the arc will very likely be extinguished. The sudden decay or undershoot of current will give the same result, the worst case being a combination of the sudden peak voltage rise with a marked current undershoot. These characteristics are a direct

result/...

result of the nature of the D.C. arc load which is described in more detail in a later section, after further tests have been performed.

In order to improve the welding action and produce a stable arc while welding, it is necessary to counteract the two undesirable characteristics mentioned above. As the arc length determines the welding voltage, the recovery voltage attained after a short circuit will depend on the operator's ability to maintain a constant arc length while welding. If this is adjusted to keep the welding voltage between 20 and 30 volts then the recovery voltage after a short circuit will be in the range 20 to 40 volts which is acceptable for normal welding conditions. It is thus an easy matter to control the maximum recovery voltage while welding but the control of current undershoot presents a different problem. All the tests carried out in this and the next section are aimed specifically at improving this current undershoot to give a satisfactory welding action.

(b) Rec. 6.2 shows that for a rapid current undershoot the arc will be extinguished as the current falls to zero. In this trace the arc remains out for approximately 50 mS. and the voltage begins to return to the normal open circuit value. Automatic restrike occurs and the current increases rapidly and returns to the normal welding value. However the time that the arc had 'snuffed out' is sufficient to cause a discontinuity in the weld metal.

(c) Rec. 6.3 shows the transient response of the machine to a short and open circuit made with the welding electrode.

At short circuit the current transient peak is approximately three times normal current and this decays with a time constant of about 20 mS. The current undershoot indicates an underdamped system which explains the undershoots obtained when welding.

The open circuit point is not clearly defined due to arcing of the electrode, but the voltage rise has a time constant of approximately 60 mS.

6.2 COMPARISON TESTS ON A D.C. MACHINE WELDER

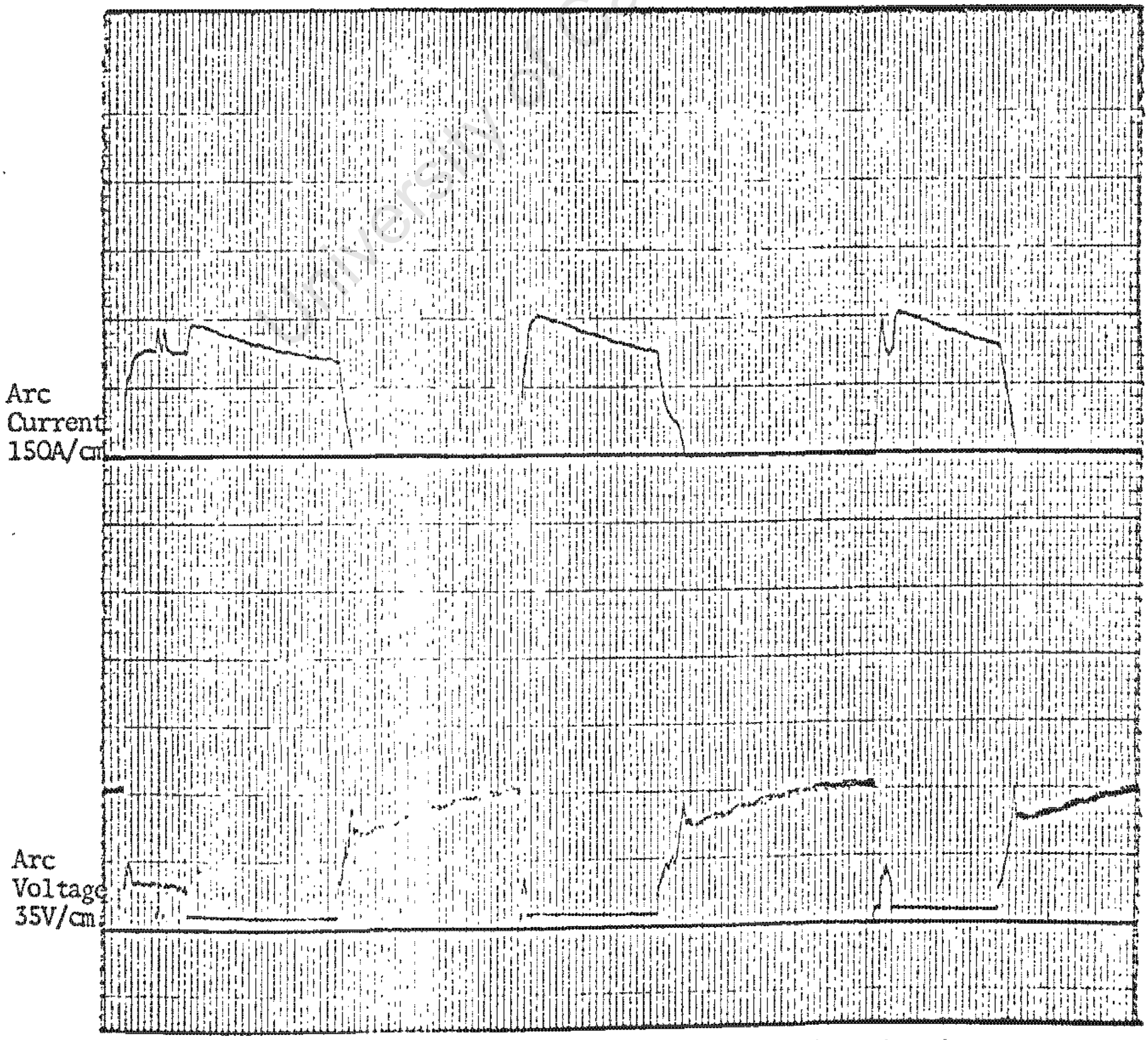
In order to gain some knowledge of what the current and voltage waveforms of an existing D.C. machine welder are like tests were performed on the 'Murex' D.C. arc welder in the Mechanical Engineering Department's Workshop. Traces of arc voltage and current were taken for a typical weld, the top D.C. field current waveform being omitted in this case owing to the inaccessible position of the winding in the machine.

(a) Rec. 6.4 shows the dynamic characteristics of a typical D.C. machine welder.

The current changes in this recording are considerably more damped than in Rec's. 6.1 and 6.2 and have only a small undershoot compared with the marked undershoot obtained with the brushless welder. There is still, however, current overshoot at short circuit which is desirable so that the molten metal drop shorting the arc will quickly be removed.

Rec. 6.4

Time-10mS./div.



Rec. 6.5

Time-10mS./div.

The voltage waveform is very similar to that of the brushless welder; arc voltage depending largely on the arc length, which is controlled by the operator.

(b) Rec. 6.5 is a series of short and open circuits made with the electrode to investigate the D.C. machine's transient response. The current rise is very rapid but with a slow decay to the steady value. At open circuit the current falls to zero within 10 to 20 mS. and the transient voltage rise is followed by a gradual increase to the open circuit value.

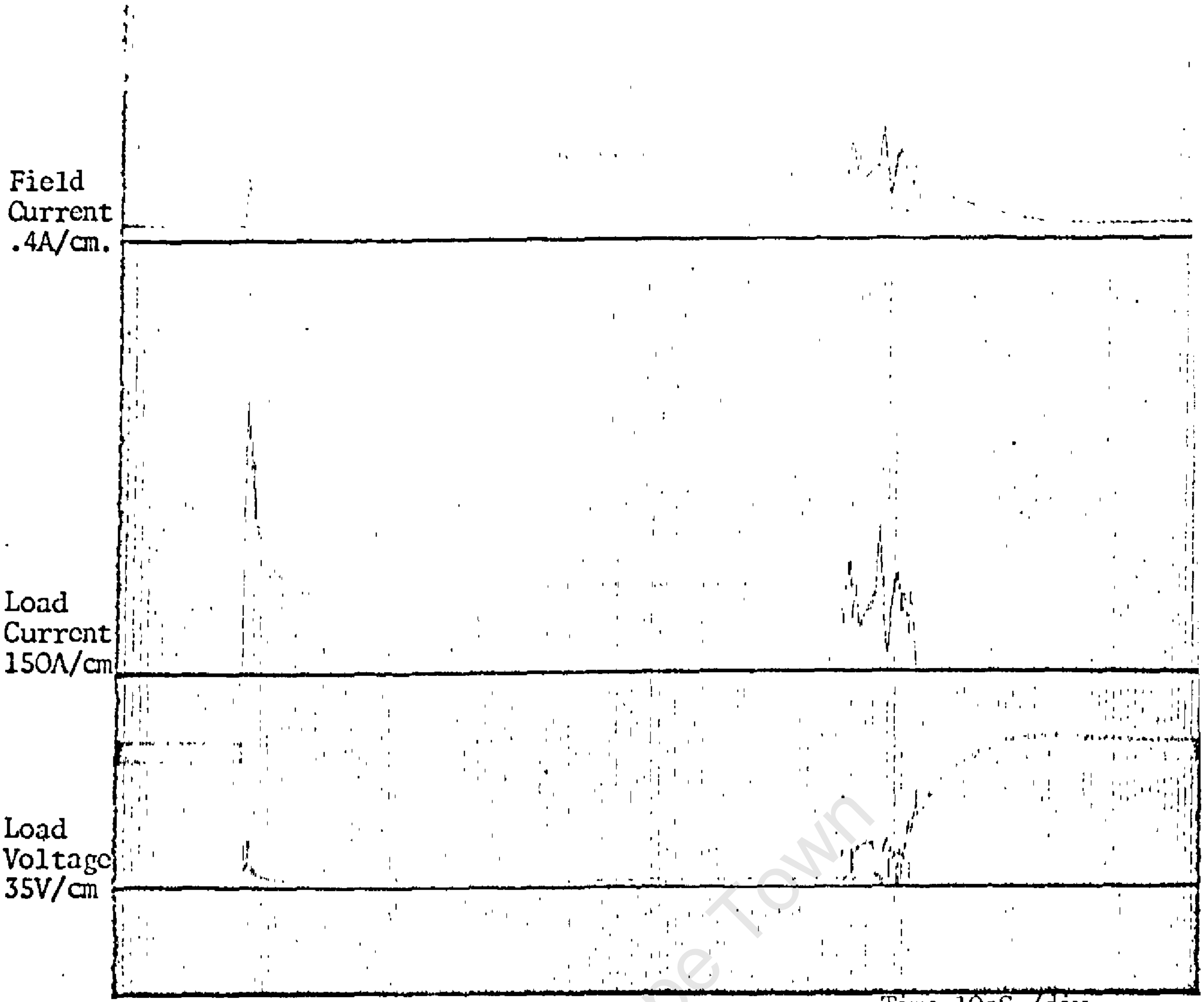
These characteristics indicate that the machine has a fast response to short circuit conditions but a relatively slow response to open circuit conditions, making it suitable for welding with good arc stability. The current overshoot is not too severe with a damped rise to the maximum and so metal spatter is not a problem here as in the case of the brushless alternator welder.

(c) Rec. 6.6 gives the transient response to a single short and open circuit on the 'Murex' D.C. machine welder.

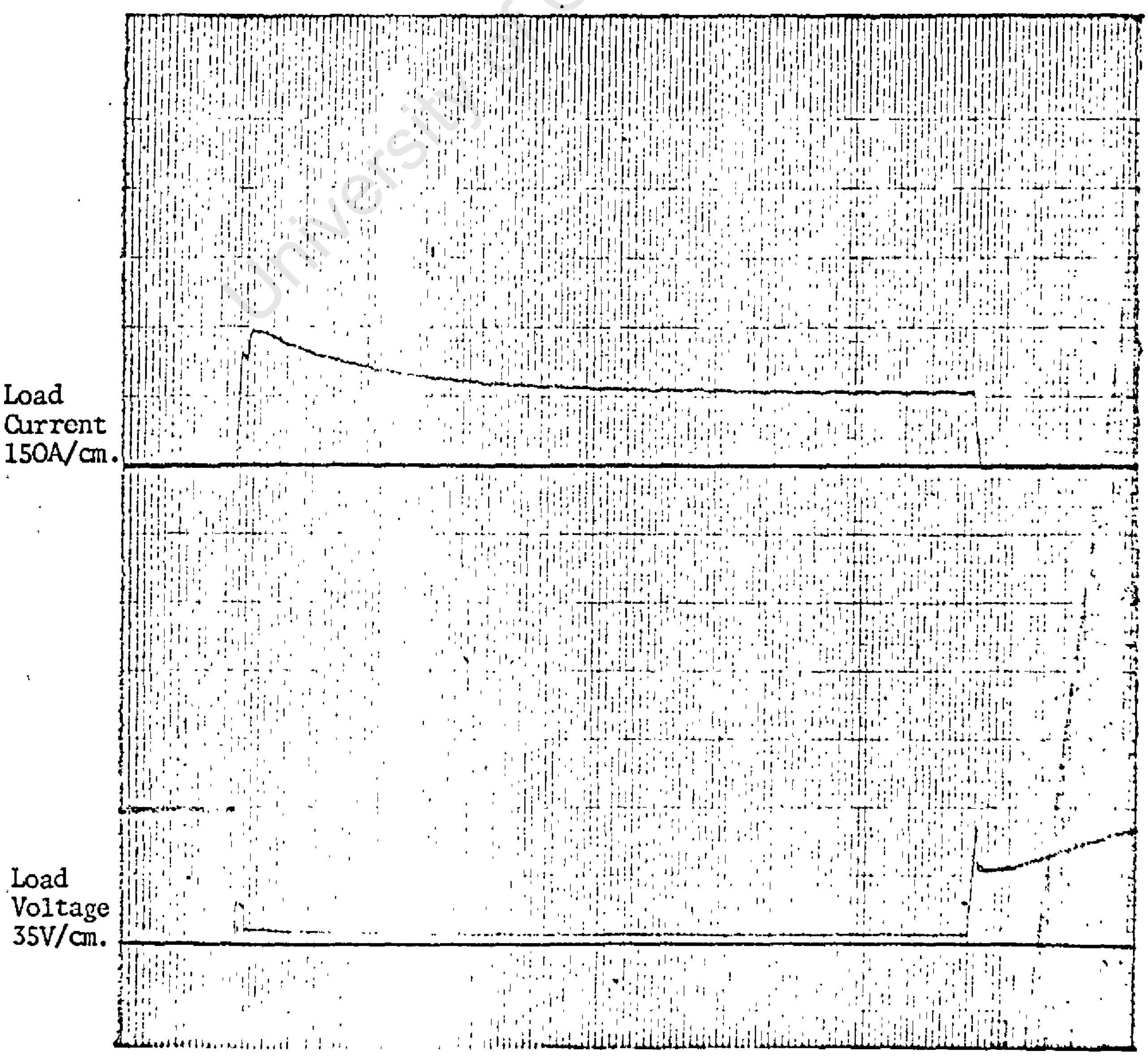
The current rises to approximately twice normal short circuit current and decays with a time constant of about 200 mS, which is 10 times that for the brushless welder.

On open circuit the voltage rises sharply almost to the open circuit value and then falls to half this

value/...


Field Current .4A/cm.
Load Current 150A/cm
Load Voltage 35V/cm
Time-10mS./div.

Rec. 6.3


Load Current 150A/cm.
Load Voltage 35V/cm.

Rec. 6.6

value before rising again to full voltage. The rate of rise is slow, with a time constant of approximately 200 mS, as before with current decay.

These tests on the commercial D.C.machine welder thus indicate that the time constant of the system for the brushless welder needs to be increased somewhat in order to produce satisfactory welding with the necessary arc stability.

7. EXCITATION CIRCUIT MODIFICATIONS

All the modifications and additions to the excitation control circuit described in this section are intended to increase the time constants of the system and limit the current undershoot after a short circuit, so as to prevent any 'snuffing out' of the arc.

7.1 ADDITION OF L AND C ELEMENTS

Inductive and capacitive components were connected to the field circuit as follows:

(a) Series inductance in field circuit. (L/R time constant).
As the exciter field inductance is approximately 1 Henry, a D.C. choke of similar value was connected in series with the field winding to increase the time constant. This however had no effect on the D.C. output current waveform and very little effect on the field current waveform. No improvement in weldability resulted and the arc was still unstable.

(b) Shunt capacitance in field circuit. (R.C. time constant).
Capacitors up to 100 μF were connected in shunt across resistors RA and RB and RC of the field excitation circuit of Fig. 4.1. Again, this had no effect on output currents waveform and arc stability was not improved.

7.2 ADDITION OF DIODE ELEMENTS

(a) In order to suppress fast negative current changes

diodes/...

diodes were connected in shunt across the field winding and across RB with corresponding biasing for normal steady state operation. This addition had negligible effect on the output current waveform and arc instability was still present.

(b) A series diode and shunt capacitor were connected into the field circuit to increase the time constant and prevent negative current undershoots when the arc voltage recovers. Again this had no effect on the current waveform and arc stability. A series diode and capacitor connected in shunt across the field winding made no improvement to the time constant either.

(c) A shunt capacitor across R6 and shunt diode across RB as shown in Fig. 7.1 did improve arc stability slightly. When the arc is shorted by a molten metal drop the capacitor across R6 will discharge into the field circuit through the shunt diode across RB, this being the path of least resistance. On the subsequent open circuit of the arc, when the drop disappears, the capacitor charges up with time constant R6.C which tends to increase the field current decay time constant. This is shown in Rec. 7.1 which gives the current through the shunt capacitor across R6. The positive spikes represent the discharge current at short circuit and are of very short duration. The negative spikes show the charge-up current of the capacitor and have a longer time constant. The field current waveform does show an increased time constant but the amplitude of the spikes has no effect on the waveform due to the large

inductance/...

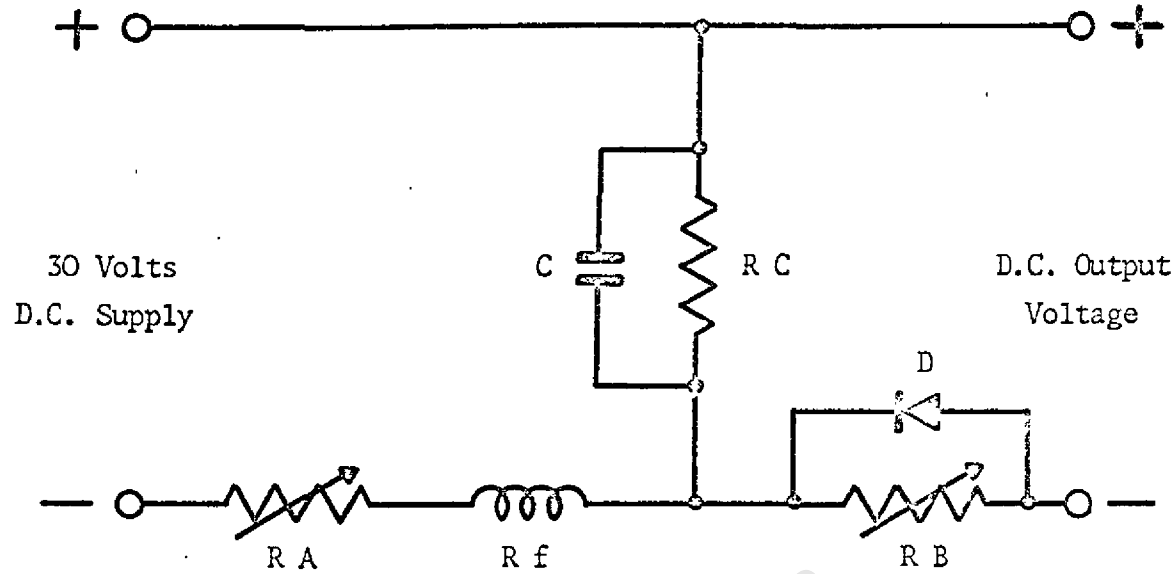


Fig. 7.1 Control Circuit Diagram with Shunt Capacitor and Diode additions.

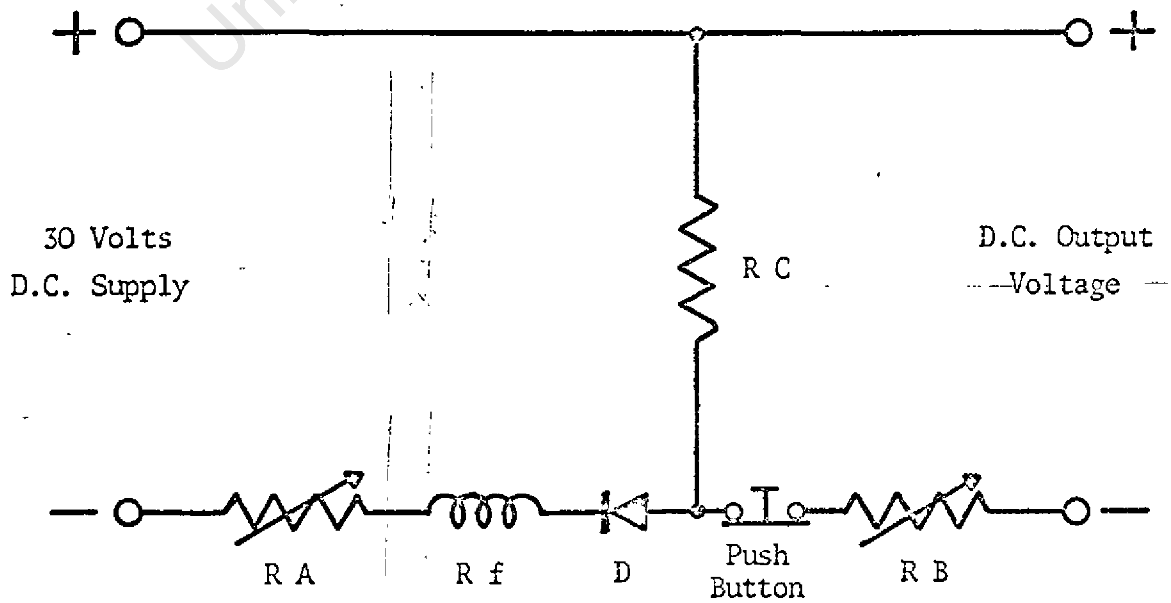
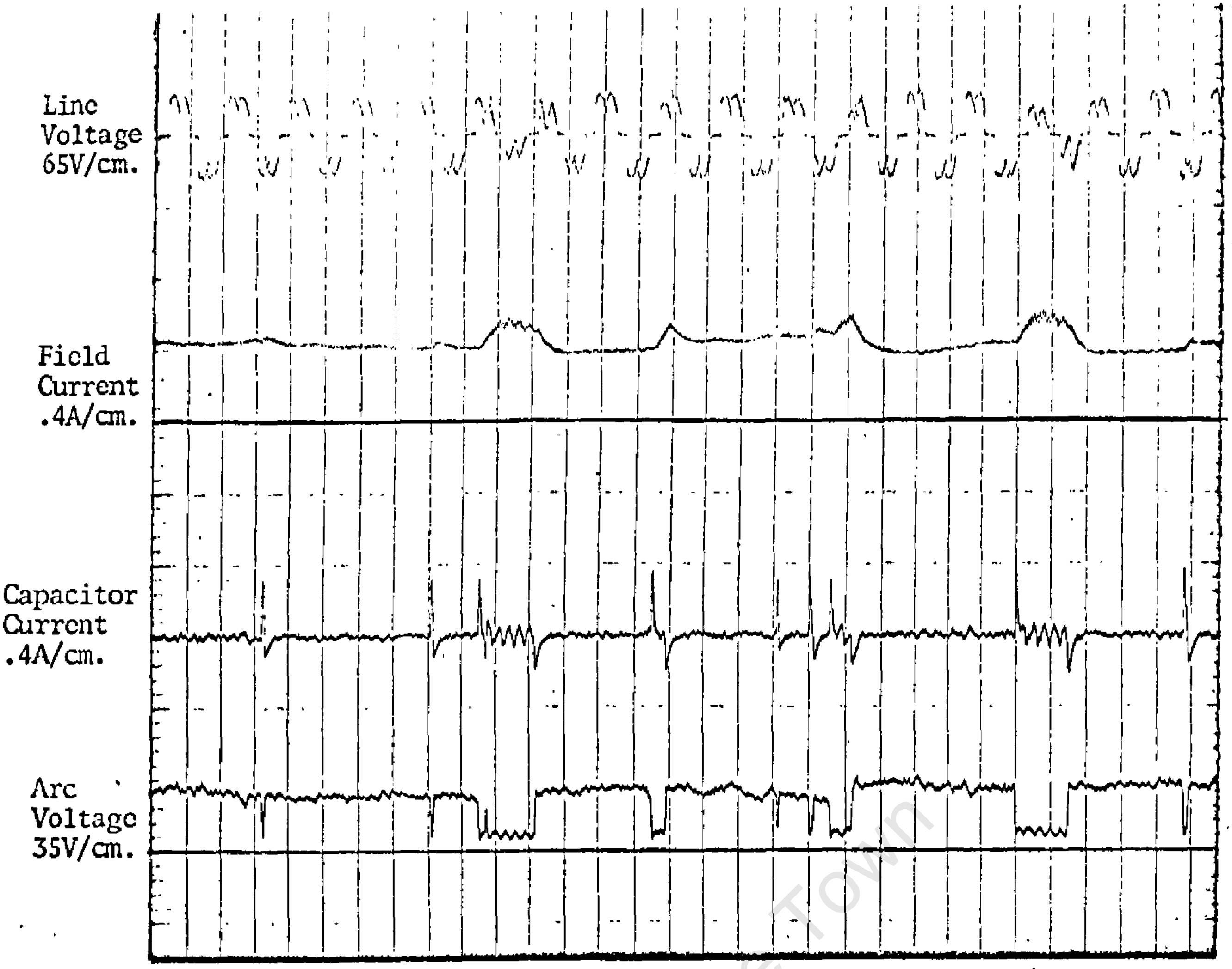
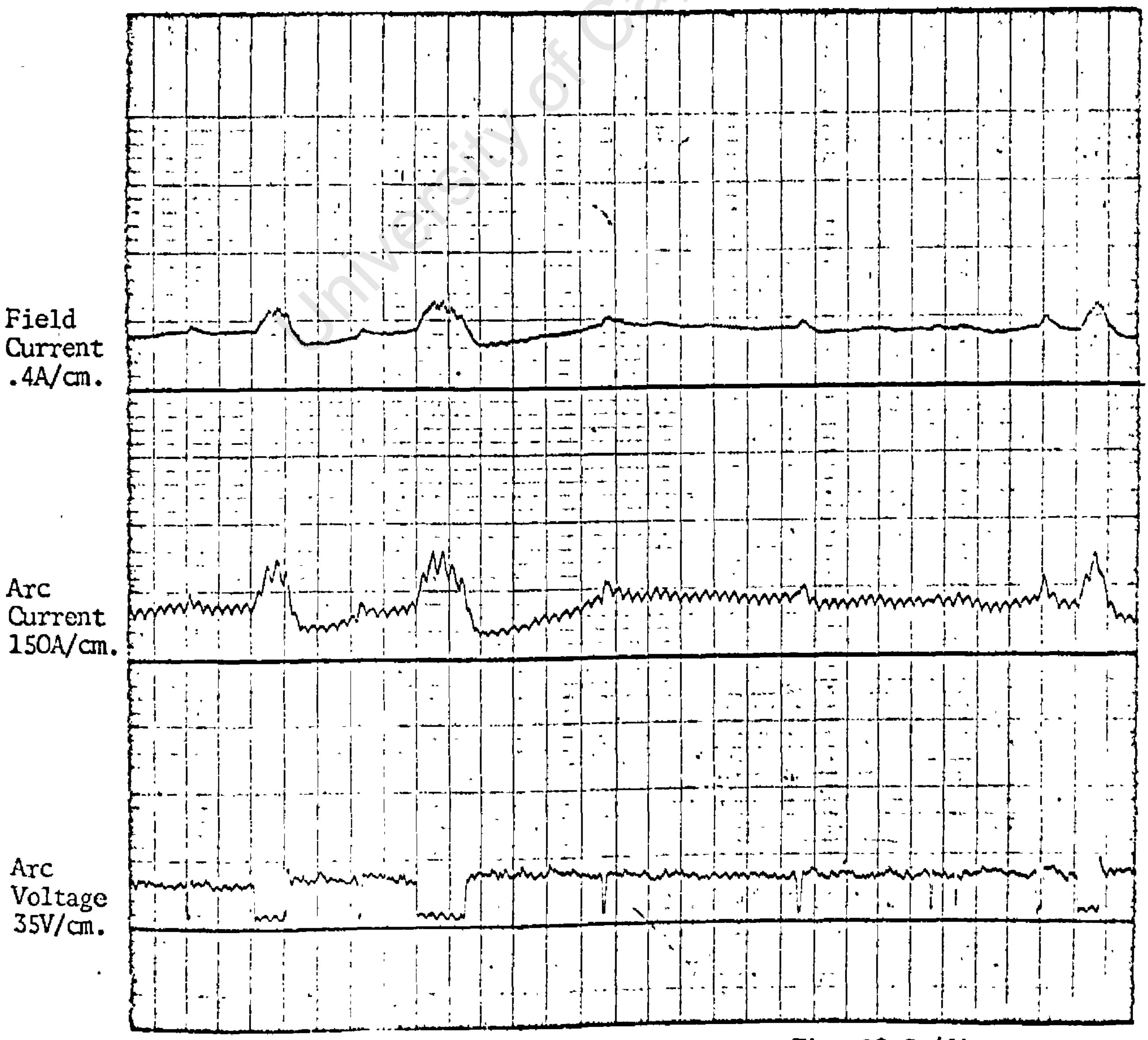


Fig. 7.2 Control Circuit Diagram with Series Diode and Push Button.



Rec. 7.1

Time-10mS./div.



Rec. 7.2

Time-10mS./div.

inductance of the field. The arc current waveform is given in Rec. 7.2 and shows a reduction in the current undershoot after the open circuit of the arc.

The weldability and arc stability are improved but still not to an acceptable level for use in industry.

The conclusions to be drawn from the above sub-sections are that it is not possible to increase the time constant of the system by changing the components of the field excitation circuit as originally hoped. This would have been the simplest method to obtain arc stability but as it appears that the control changes in the flux of the excitation circuit take too long to effect the main stator circuit, a different method will have to be used.

It is therefore necessary to consider increasing the time constant of a different part of the system. The output circuit of the alternator is directly connected to the arc load so this would be a likely part to consider.

7.3 ADDITION OF L IN OUTPUT CIRCUIT

Another method whereby the time constant of the system may be increased is to add inductance in the power output circuit of the welding generator. A D.C. choke placed in series in one of the output welding lines actsas an energy store and will tend to maintain the current flow through the winding.

The choke used for the test consisted of two small open ended iron core reactors connected in series. The combined reactance measured approximately 0.6 mH at 50 Hz and there was no problem with saturation, the chokes being without a complete iron path and thus effectively air-cored reactors.

The/...

The weldability and arc stability with this modification were much improved but still not entirely satisfactory, being unacceptable to operators for industrial use.

Rec. 7.3 shows the marked current undershoots obtained when welding without a choke in the output line. Great difficulty was experienced in producing a satisfactory weld without 'snuffs' in this case.

There is a significant reduction in the current undershoots when welding with the D.C. choke in the output line, as illustrated in Rec. 7.4. Here the arc length has been kept to a minimum so that the arc is frequently shorted out by the metal drops and the current response can be easily seen for each short circuit.

The field current waveform closely resembles the output current waveform as in Rec's. 7.2 and 7.3 and it now seems likely that the transient changes of the field current are dependant entirely on the transient changes of the welding arc current.

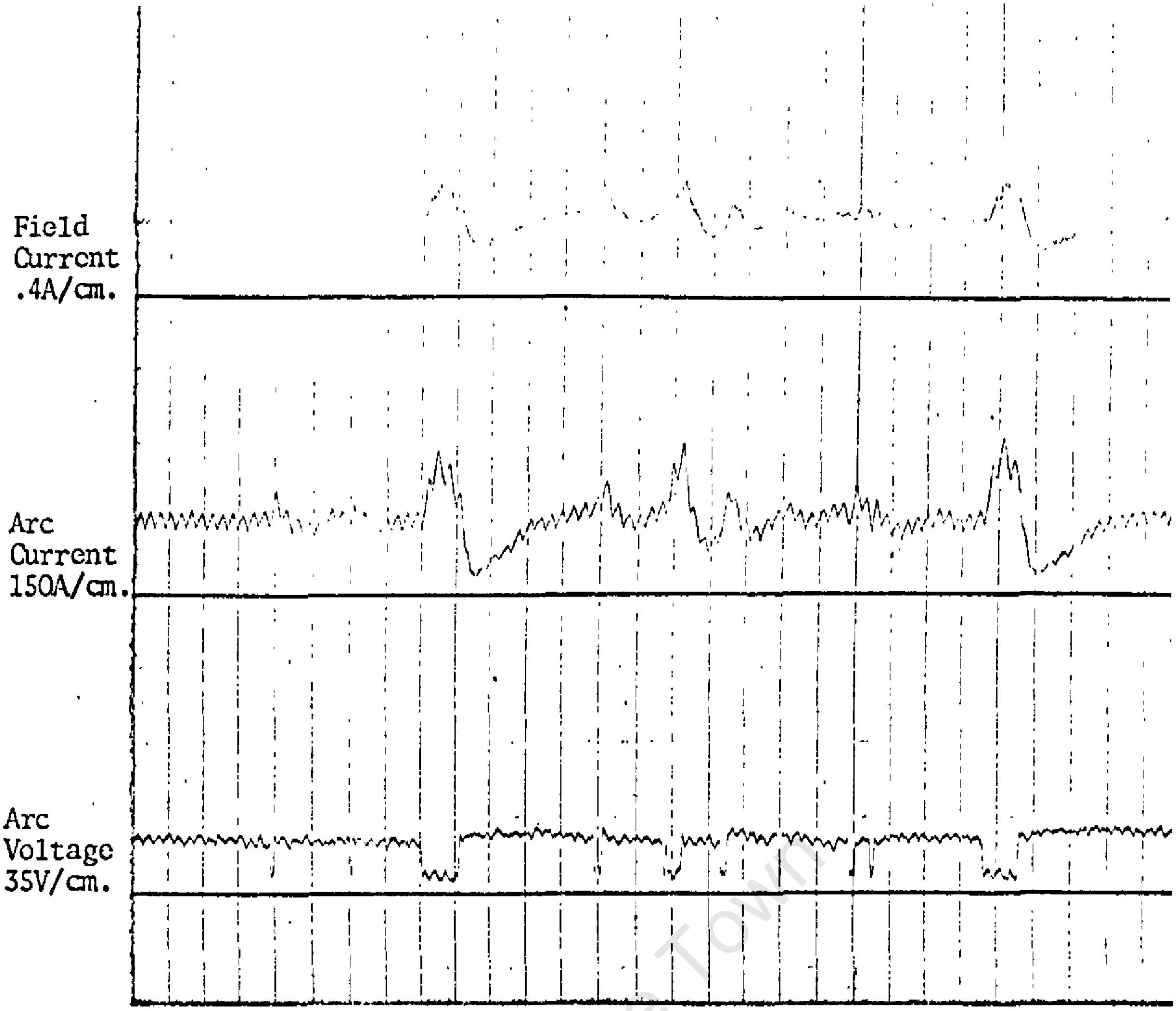
7.4 FIELD EXCITATION TRANSIENTS

The following tests were carried out on the system to determine how the alternator output current changes affected the field excitation current waveform for transient loads.

7.4.1 WITHOUT VOLTAGE FEEDBACK

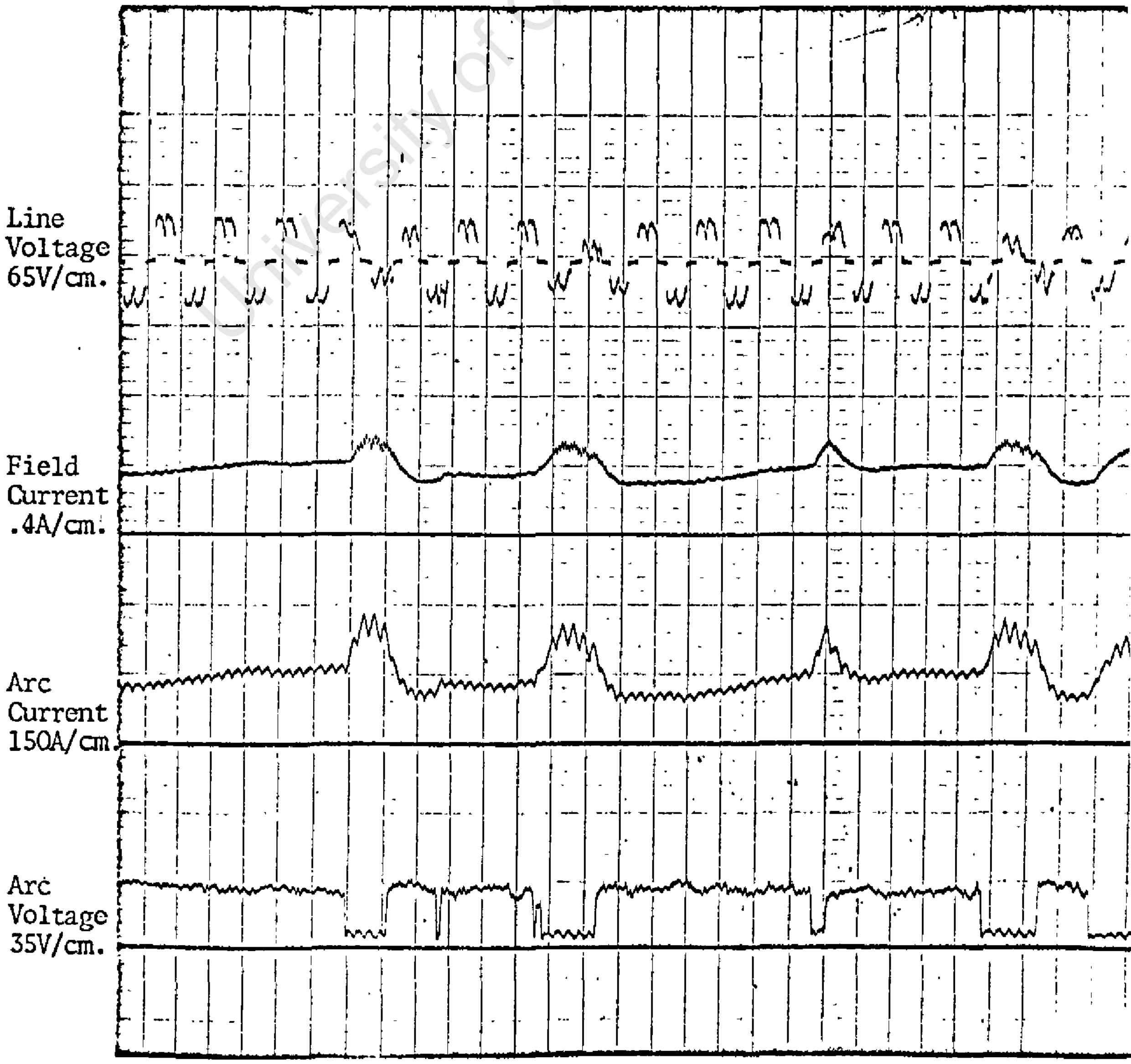
To achieve isolation between the field excitation circuit and the D.C.output circuit a switch is incorporated in the feedback path through resistor RB of Fig. 7.2. This switch can only be opened while welding. On open circuit with a set voltage,

opening/...



Rec. 7.3

Time-10mS./div.



Rec. 7.4

Time-10mS./div.

opening the negative feedback path will cause the voltage to increase to twice its value and reach a dangerous level.

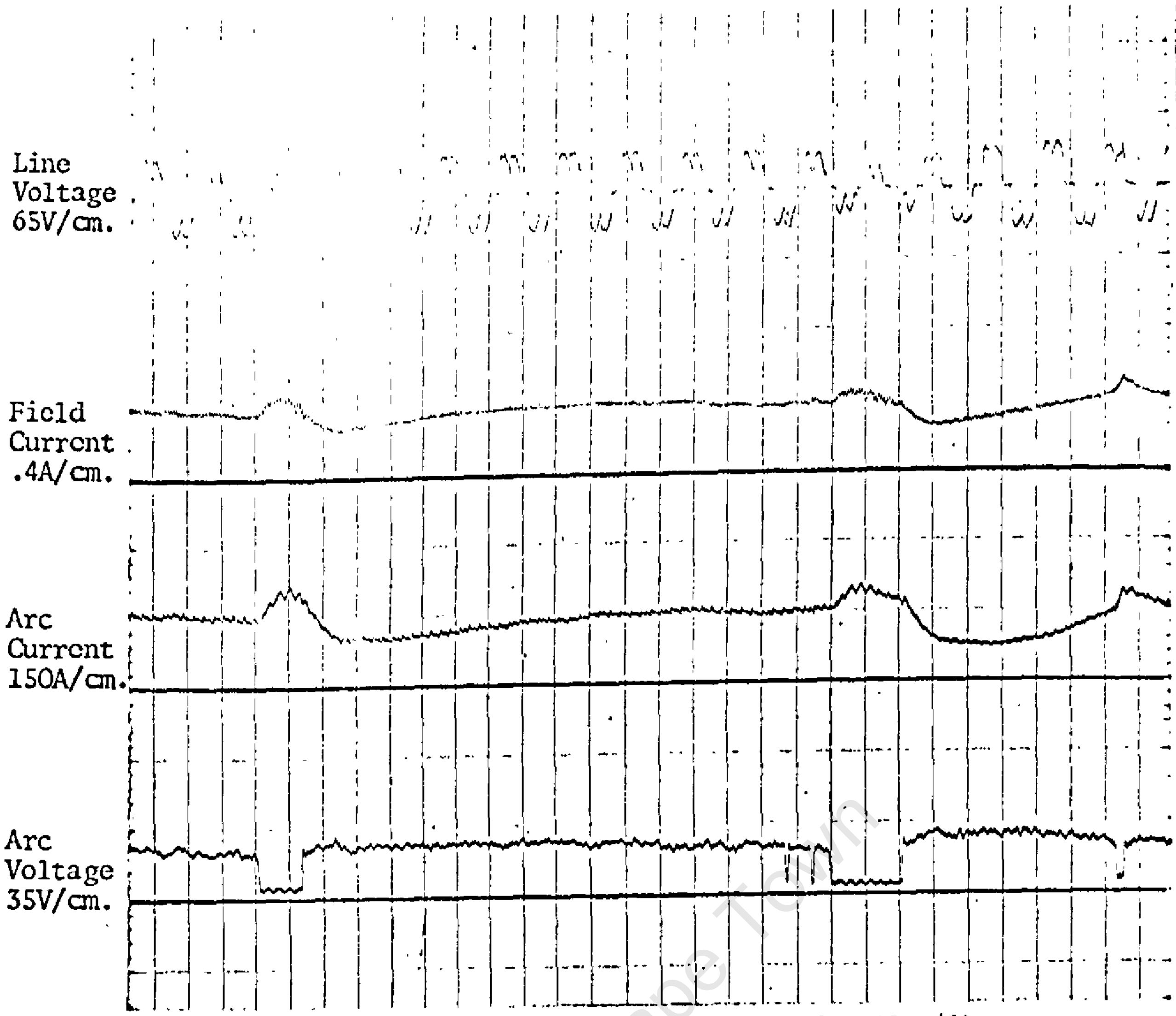
Calculations show that the field current will increase by approximately 30% when the feedback switch is opened, but this is not serious as the D.C. arc current will only increase slightly.

It was found necessary to connect a series diode in the field circuit to prevent the field current reversing direction when the voltage feedback switch was reclosed. This would produce a high reverse transient excitation current, due to the increased voltage on open circuit without voltage feedback. A reversed field current would thus make the resulting voltage feedback positive and possibly damage the alternator windings with increased loading at an extreme voltage.

Traces of current and voltage when welding without voltage feedback are given in Rec. 7.5. The arc current waveform indicates that there is still undershoot after a short circuit and the field current waveform resembles closely that of the arc current. Thus the arc current transients influence the field current to a great extent and the arc voltage transients have negligible effect on the field current. It is now apparent that increasing the time constant of the exciter field does not have the desired effect on the system as was originally expected.

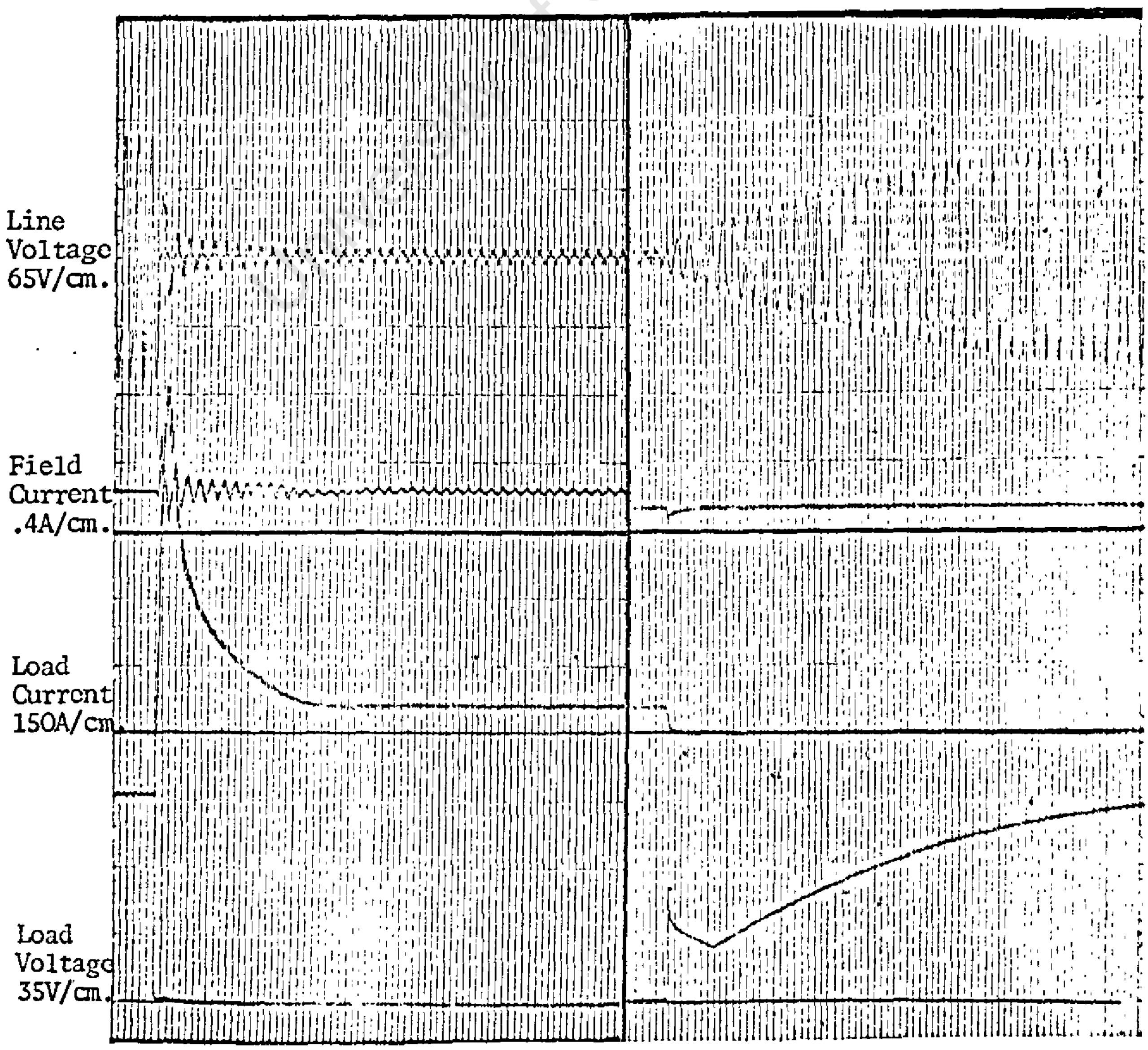
From Section 7.3 the system time constant for transient loads can be increased by adding inductance in the

output/...



Time-10mS/div.

Rec. 7.5



Rec. 7.6 a & b

Time-10mS/div.

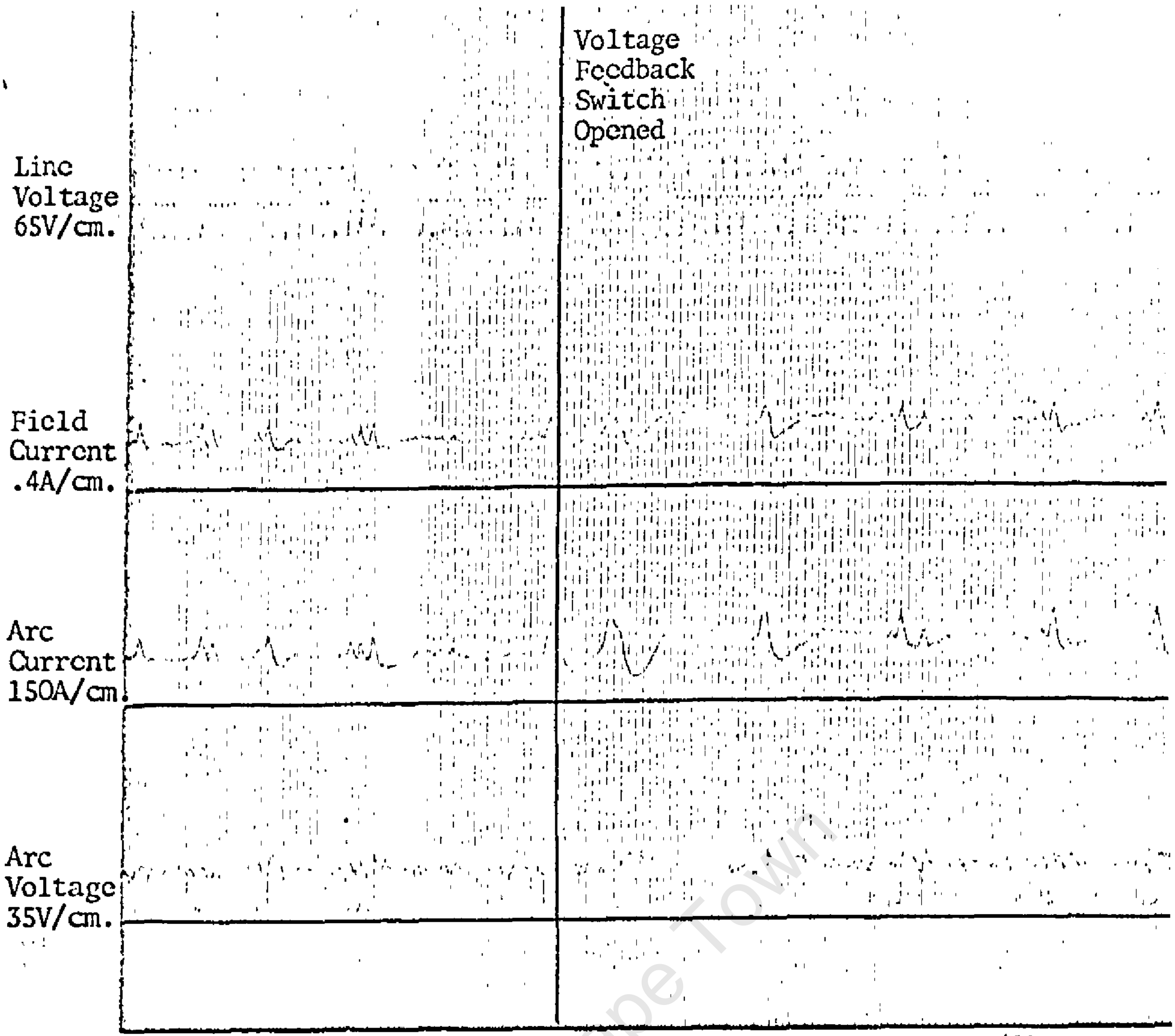
output of the alternator and this seems to be the only practical method to obtain suitable weldability and arc stability.

The transient response of the system to a short and open circuit is given in Rec. 7.6 (a) and (b). The arc current has an initial transient peak of approximately 12 times the normal steady state value for a short circuit. The current decays with a time constant of 50 mS and has a slight undershoot indicating underdamped conditions. At open circuit the current falls to zero immediately and there is a corresponding dip in the field current waveform. This shows conclusively that it is the arc current transients which affect the field current and not the associated arc voltage transients from the feedback circuit.

7.4.2 WITH NEGATIVE VOLTAGE FEEDBACK

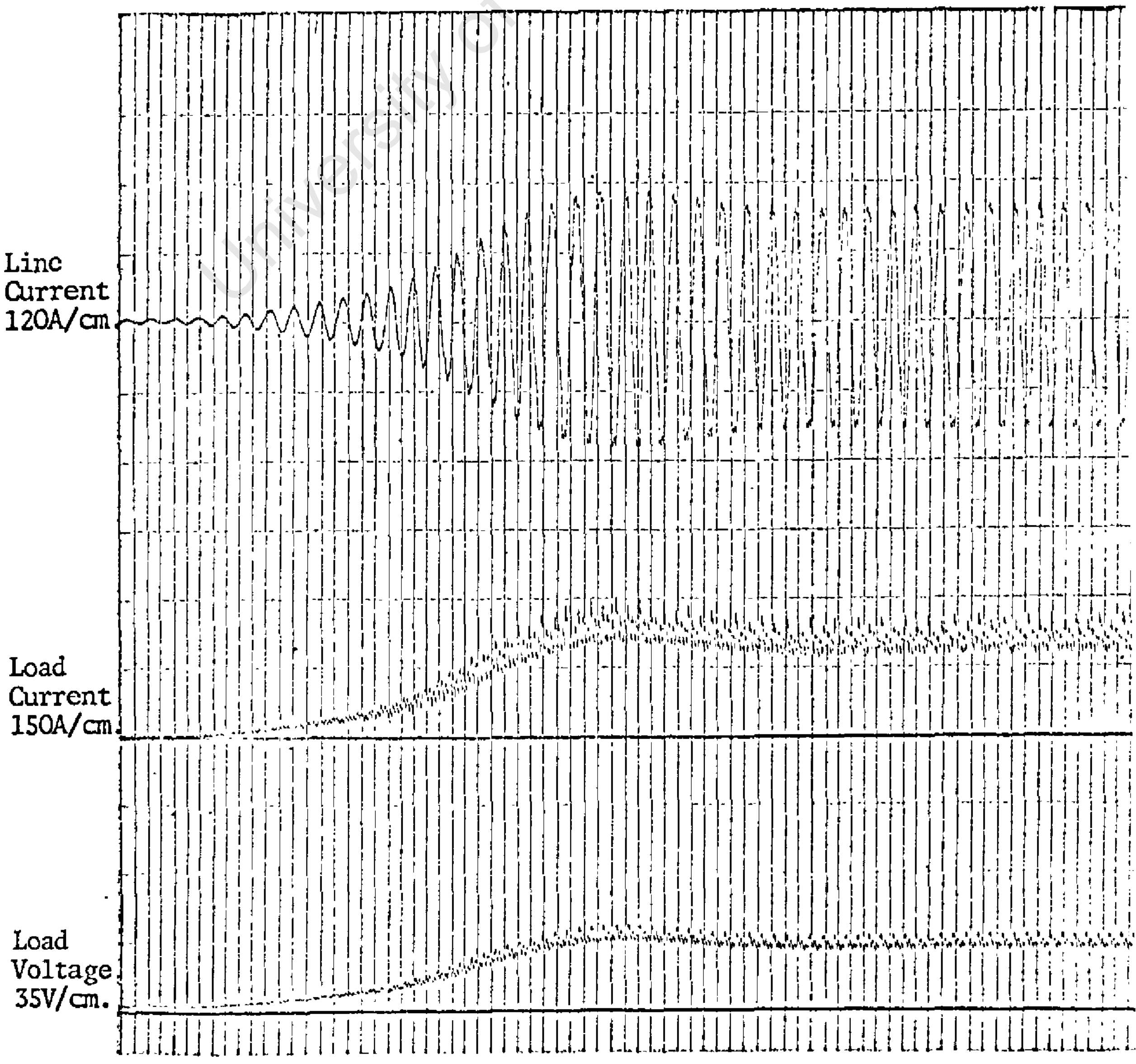
The initial welding characteristics determined in Section 6 were investigated using negative voltage feedback in the exciter field circuit. The relationships between exciter field current and arc current are shown in Recs. 6.1 and 6.2, there being much similarity between the two waveforms.

An interesting comparison between waveforms of exciter field current with and without negative voltage feedback is given in Rec. 7.7. The feedback isolating switch has been opened at the point marked and the exciter field current and arc currents have increased slightly. The arc current undershoots appear to be worse without feedback but in this case the duration of arc shorting is relatively longer



Rec. 7.7

Time-10mS./div.



(25-30 mS) than for the first part of the trace with voltage feedback (5-10 mS). For arc shorts of equal duration the undershoot is approximately the same in both cases. Note also the similarity between arc current and field current waveforms without voltage feedback; the recording shows no difference in the waveforms with or without voltage feedback. This is due to the tight coupling between the magnetic circuits of the main stator winding and the field exciter stator winding. The frame of the machine is common to both stator yolks and thus forms a magnetic path link for the main flux to have a mutual effect on the exciter flux.

Rec. 7.8 shows the system time constant for voltage and current build-up when the field excitation is switched on. This time constant is approximately 200 mS thus indicating a long interval for a field current change to have an effect on the output current.

These tests confirm that transient changes in the field excitation circuit have no effect on the output from the alternator. Further tests carried out in a later section on the machine's transient characteristics also confirm this conclusion.

8. D.C. ARC CHARACTERISTICS

The Electrical Characteristics of the D.C. Welding Arc are the most important factors which influence the design of the welding generator. As described in Sections 1, 6 & 7, it is the transient characteristics of the system which determine the weldability and arc stability of a welder and the arc characteristics in turn affect the system's transient response.

8.1 METAL TRANSFER ACROSS THE ARC

8.1.1 WELD METAL DEPOSITION

A brief description of the mechanism of welding and weld metal deposition has been given in the Introduction, Section 1.3. Fig. 1.1 shows how the metal transfer takes place across the arc, and the various physical and chemical factors involved will not be discussed here.[1]

Section 1.4 (b) describes the metal transfer as a stream of molten metal droplets of various sizes. Some of these droplets are large enough to short circuit the arc and cause the arc voltage to fall almost to zero.

The arc characteristics are thus divided into two types; static and dynamic as with the characteristics of the welding generator, described in Section 1.4. As in the case of the generator the dynamic arc characteristics affect the weldability and arc stability of the welder as they determine the type of transient load on the generator. The two important factors affecting the dynamic arc characteristics are the frequency and duration of the shorting of the arc by the molten metal drops.

8.1.2/...

8.1.2 FREQUENCY AND DURATION OF ARC SHORTING

This is dependant on a number of physical and chemical properties, some of which can be controlled by the operator.

(a) Type of Welding Electrode

The electrodes or filler rods used for arc welding are of two basic types, covered and bare electrodes. Covered or shielded metal electrodes are used extensively in industry, whereas bare metal electrodes are used only for special applications. Thus most electric arc welding is of the shielded metal-arc type as shown in Fig. 1.1.

The frequency and duration of arc shorting is greater in the case of bare metal electrodes owing to the absence of the arc shield which controls the metal deposition to a large extent. There is a possibility with certain covered electrodes having a rapid liberation of gases at the tip, to form bubbles of molten metal. These may burst with high pressure or expand until the arc has been shorted, and then be blown away by the current surge at short circuit.

(b) Arc Length

A short arc length results in increased frequency and duration of arc shorting. The arc length is controlled by the operator and must be maintained at the correct length. If too short, the frequency of short circuiting will be too high and produce an uneven deposition

of/...

of weld metal but if too long the arc becomes difficult to control and guide on a precise path. Deposition of weld metal with a long arc can also be erratic and uneven, although the frequency of short circuiting is much reduced.

(c) <u>Arc Blow</u>

Erratic deposition of weld metal with a slightly longer arc than normal may also be due to magnetic arc blow. This is a phenomenon found mainly in D.C. arc welding and is caused by the magnetic fields set up around the electrode when the arc current is flowing through the electrode and workpiece. These fields tend to deflect the arc from its intended path either sideways or, more often, in a forward or backward direction along the line of travel. The arc blow is usually directed away from the point where the ground terminal is connected, and if it should become excessive a satisfactory weld cannot be made. In general the arc blow will be in a direction away from areas of flux concentration such as the ends of the workpiece and steps must be taken to avoid the increased arc blow at the ends of the weld. These may include reducing the current and hence the magnetic field strength or keeping the arc length as short as possible. The shielded metal electrode assists in holding a short arc as the projecting covering on the electrode will give a minimum arc length when held against the workpiece while welding. This, of course, will increase the frequency of arc shorting but is acceptable in this case where arc blow is a problem.

(d)/...

(d) Current Setting

For high current settings the size of the molten metal droplets increase with larger electrode sizes. If the current is too high for a particular rod the frequency of short circuiting of the arc will increase but the duration will decrease owing to the excess current at short circuit which blasts the metal droplets from the arc.

Should the current be too low for a particular rod the frequency of shorting decreases but the duration will increase due to the lower current at short circuit.

High current settings result in increased metal spatter which causes erratic deposition and an unsatisfactory appearance of the weld metal. Low current settings cause insufficient deposition of weld metal and lack of penetration. A Shorter arc is necessary at low currents and thus the duration of arc shorting increases.

(e) Speed of Welding

Factors affecting the speed of welding include the current setting and the deposition rate of the weld metal. These have already been discussed but generally a fast welding speed will decrease the frequency and duration of the arc shorting by the metal droplets.

Although these arc characteristics affect the transient response of the system to a large extent, they have been discussed at this stage as it was necessary to get some idea of the mechanisms involved in arc welding, before attempting a detailed description of the characteristics of the electric arc.

8.2 ARC RESISTANCE

The arc resistance characteristics are the most important factors which influence the design of the welding generator and hence the weldability and arc stability during the welding operation.

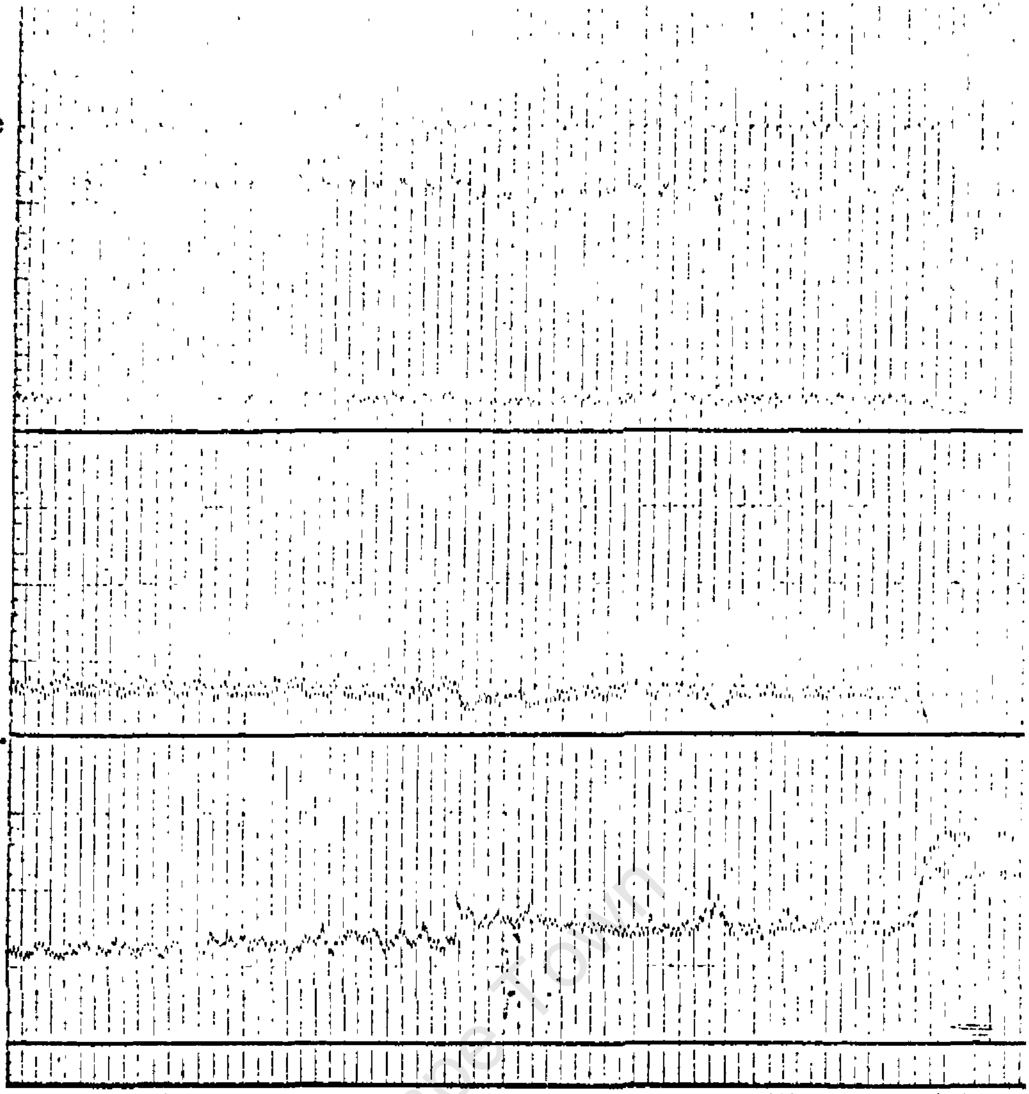
The characteristics are divided into two sections, namely the static and dynamic resistance characteristics.

8.2.1 STATIC ARC RESISTANCE

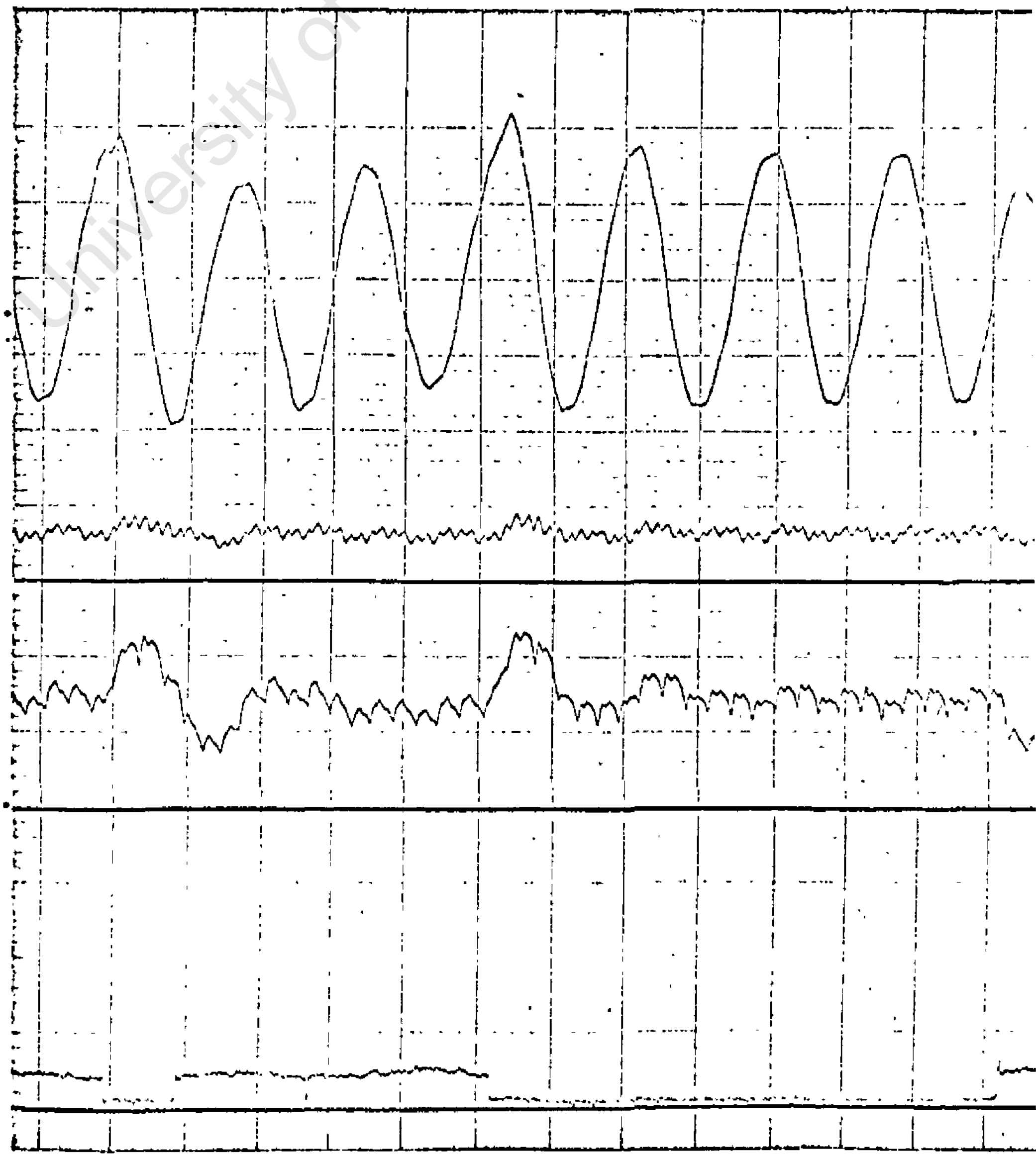
These characteristics influence the static characteristics of the D.C. welding generator and determine the shape of the desired machine characteristics described in Section 1.4.

The electric welding arc is a resistance with a negative coefficient, i.e. for increased voltage across the arc the current through the arc will decrease. This is illustrated in Recs. 8.1(a) and (b), which show the voltage and current waveforms for a weld where the arc length is gradually increased to increase the voltage across the arc. The current is shown to decrease when the voltage is increasing and at maximum voltage the current has fallen to zero when the arc is extinguished. Thus the need for maximum voltage at zero current and maximum current at zero voltage determines the type of load characteristic required by the

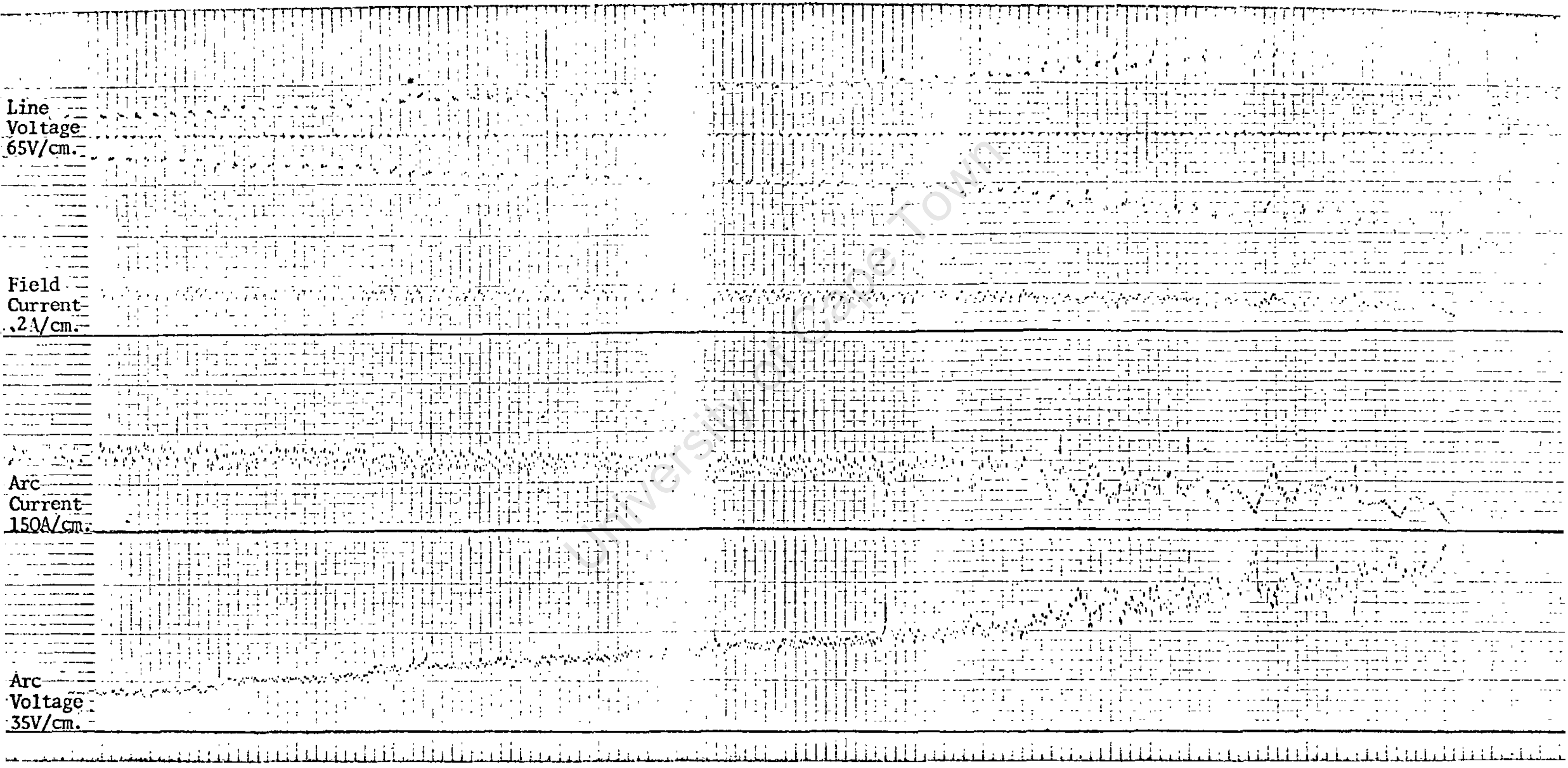
welding/...



Rec. 8.1 a.



Rec. 8.2 Time-10mS./div.



Line
Voltage
65V/cm.
Field
Current
.2A/cm.
Arc
Current
150A/cm.
Arc
Voltage
35V/cm.
Time-10mS./div.

Rec. 8.1 b.

welding generator.

Calculations of arc resistance from the voltage and current waveforms of Rec. 8.1(b) show that the resistance changes over the range of welding arc voltages. However when the values of voltage and current are plotted with the static load characteristics of the machine using the artificial arc resistance load bank, they resemble closely the characteristics as obtained in Fig. 11.5. This indicates that the arc resistance can be taken as purely resistive, neglecting the very small inductance of the load bank. In this case the resistance characteristics are linear as shown in Fig. 8.1 and the static characteristics of the machine intersect the family of arc resistance characteristics thus giving the variations in resistance for increased arc voltage.

The D.C. welding generator is basically a constant current generator and for a large change in voltage there should be only a small change in current. To maintain a constant flow of metal from the electrode to the workpiece it is necessary to have a constant current through the arc and this indicates that there should be a small change in arc resistance for any change in arc current. In this case the heat generated at the arc, being proportional to I^2R, will remain constant over the normal range of arc voltages.

As it is possible to control the arc length within close limits for automatic welding processes

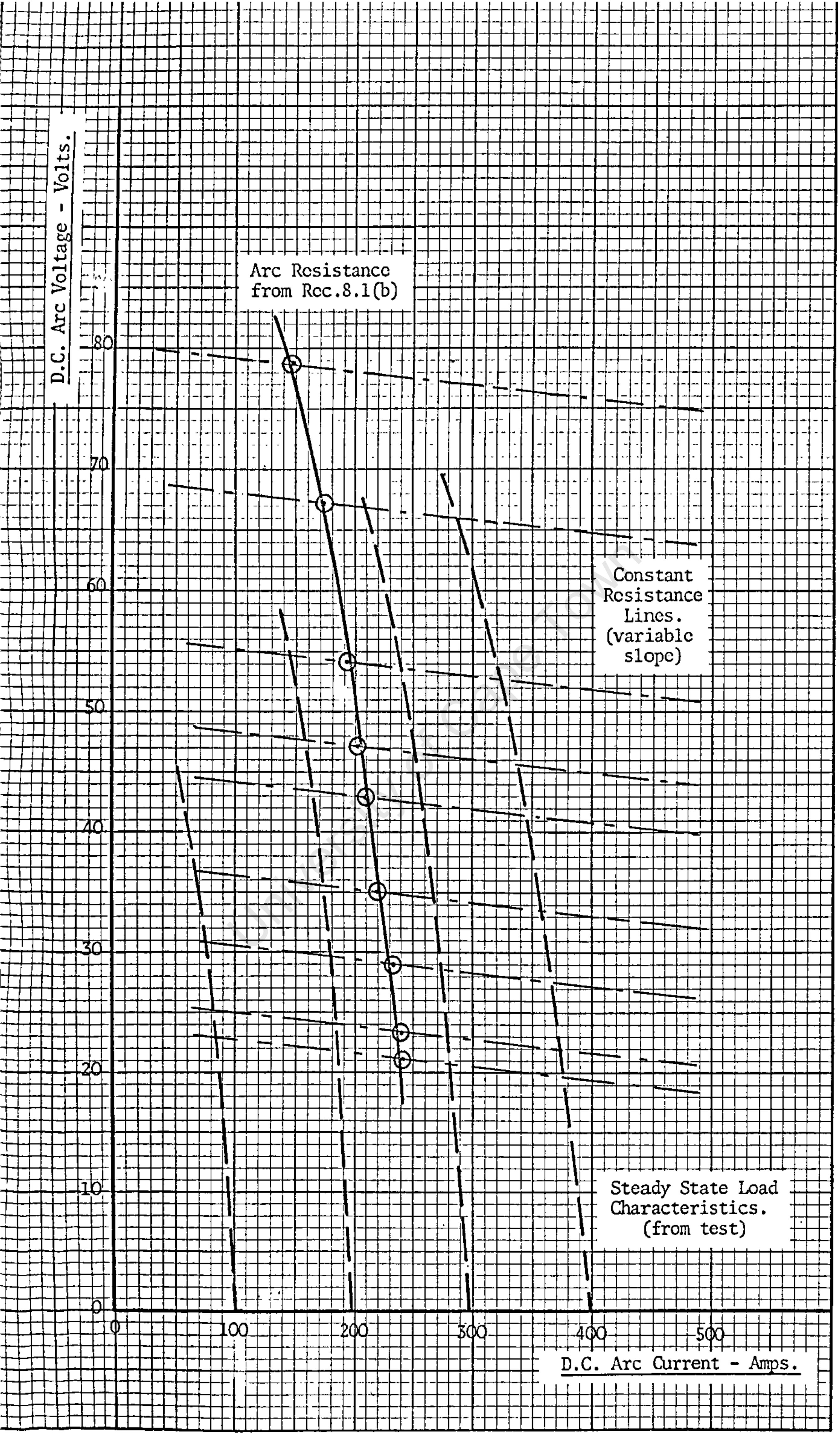


Fig. 8.1 Static Arc Resistance Characteristics.

these generators have constant voltage characteristics so giving a minimal change in arc resistance. With precise settings of welding current the heat output at the arc can be maintained at an extremely constant level and thus give a very uniform deposition of weld metal. Many manufacturing processes in industry use automatic or semi-automatic arc welding equipment to produce high quality welded components.

8.2.2 DYNAMIC ARC RESISTANCE

These characteristics influence the dynamic characteristics of the D.C. welding generator and determine the type of transient response required from the machine as described in Section 1.4.

The exact nature of the processes giving rise to the dynamic characteristics is fully described in Section 8.1 which deals with the manner in which the metal transfer takes place across the arc.

In order to determine the dynamic arc resistance a recording of the current and voltage waveforms for a typical weld is carefully studied. These are given in Rec. 8.2 and the arc resistance is calculated as the voltage varies with time, when the arc is short circuited by a molten metal drop. As the current variations at short circuit are determined by the characteristics of the machine these should not influence the values for arc resistance calculated from the recording.

Thus/...

Thus a constant current source with no transient variations must be assumed for a particular voltage waveform.

The dynamic resistance characteristic will thus closely resemble the voltage waveform with respect to time. This characteristic is given in Fig. 8.2 and approximates to a zero resistance step function. The very sharp changes in resistance, by approximately ten times, appear almost as direct short and open circuit conditions to the generator and thus represent an extreme transient load on the system. The arc voltage during normal welding operations does not approach the open circuit value in fact, as there is only a small overshoot on the normal arc voltage when a shorting drop disappears. This overshoot appears in the dynamic resistance characteristic and does affect the transient response of the machine to open circuit conditions.

8.3 ARC STABILITY

There are three important factors which control the maintenance of a steadily burning electric arc to ensure arc stability. These are:

(a) The transient characteristics of the welding generator, which have been discussed in Sections 1, 6 & 7 and will be discussed in more detail in a later section.

(b) The metal transfer across the arc, which has already been discussed in Section 8.1.

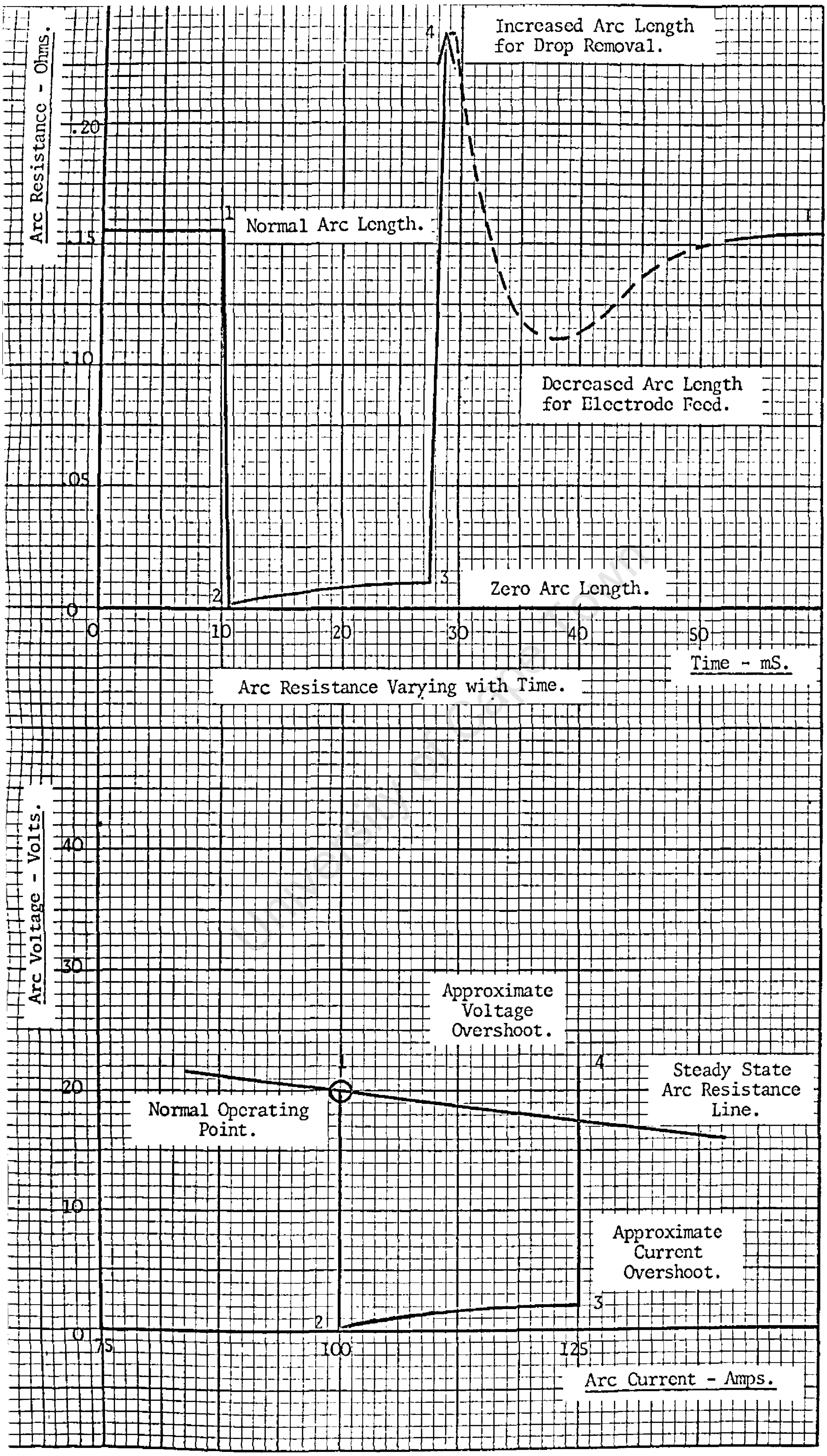


Fig. 8.2 Dynamic Arc Resistance Characteristics.

(c) The arc stream characteristics of the electrode. The electrode coatings used on the welding rods for shielded metal arc welding have a wide range of chemical properties. These coatings give off an ionized gas stream which forms the shielded atmosphere around the arc. The arc stability is thus also dependant on the degree of ionization of this gas stream which assists in the transfer of metal across the arc. The frequency and duration of shorting of the arc by metal droplets is likely to be decreased if the gas stream has a high degree of ionization.

9. CURRENT FEEDBACK CONTROL CIRCUIT

9.1 CIRCUIT REQUIREMENTS

For the following reasons it was decided to investigate the possible use of current feedback from the output in order to increase the field excitation for the higher welding currents.

(a) To avoid having to use a high D.C. voltage as the reference supply for the excitation control circuit.

As it would be a disadvantage to have to fit a separate generator to the welding plant in order to supply the high D.C. voltage, the possibility of using the 12 volt supply from the battery of the driving engine must be considered. A 12 volt battery supply is readily available on most diesel engines and the charging generator is easily capable of supplyingthe maximum current of one amp needed for the welder control circuit.

(b) To use positive feedback from the output circuit to overcome the effects of armature reaction at the higher welding currents.

The relatively low currents required by the excitation control circuit would have very little effect on reducing the output from the alternator. This system will obviate the use of a higher output stabilised supply for the control circuit at high welding currents.

(c) By having a separate current control in the feed-back loop which determines the proportion of current fed back to the control circuit, it will be possible

to/...

to have independent control of open circuit voltage and welding current for the generator.

Although the merits of current feedback control are described in the above paragraphs it must still be remembered that this system will involve the use of additional components such as transformers, diodes and resistances with consequent increase in the cost of the plant. However the advantages of current feedback are likely to outweigh these disadvantages as shown in the following sections.

9.2 INITIAL EXCITATION CIRCUIT

The first attempts at using current feedback in the field excitation circuit proved successful and the system performed as expected.

The initial excitation circuit used for the alternator is given in Fig. 9.1. A suitable Current Transformer with a ratio of 250/5 was obtained and with two conductors as the primary winding from the alternator output, gave an effective ratio of 125/5. A variable resistor, RCT, is used as the burden forthe C.T. and the voltage developed across this burden is rectified by the full wave bridge rectifier before being fed directly into the field circuit.

The feedback current is controlled by RCT and the total excitation current is in turn controlled by RA. Open circuit voltage is varied by means of RB as in the excitation circuit of Fig. 5.2.

9.3 LOAD CHARACTERISTICS

The load characteristics of the welding generator on a steady resistive load usingthe current feedback circuit

of/...

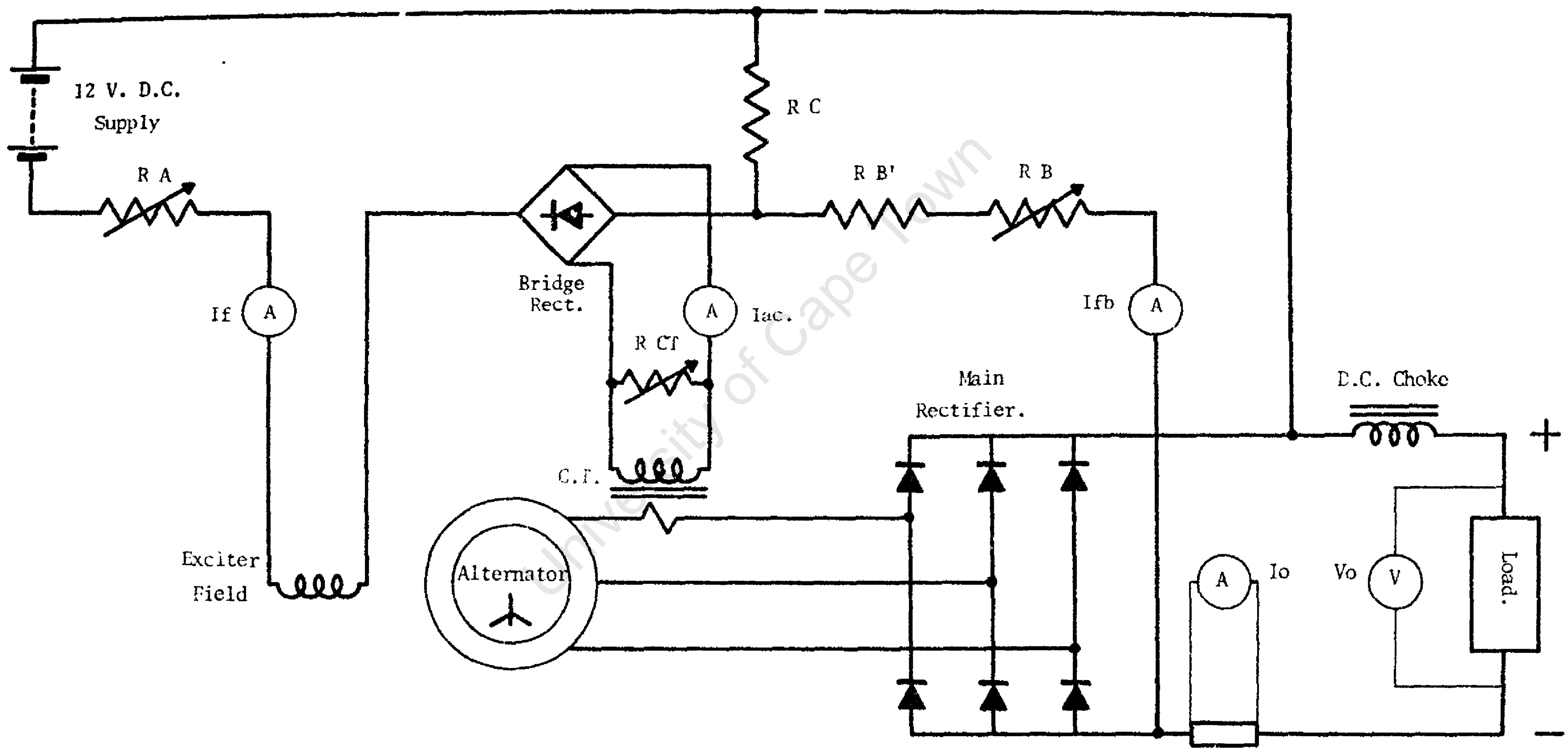


Fig. 9.1 Circuit Diagram for Load Tests with Current Feedback.

of Section 9.2 are given in Figs. 9.2, 9.3 & 9.4.

For each of these characteristics the proportion of feedback current to total excitation current is varied to give curves of different slope.

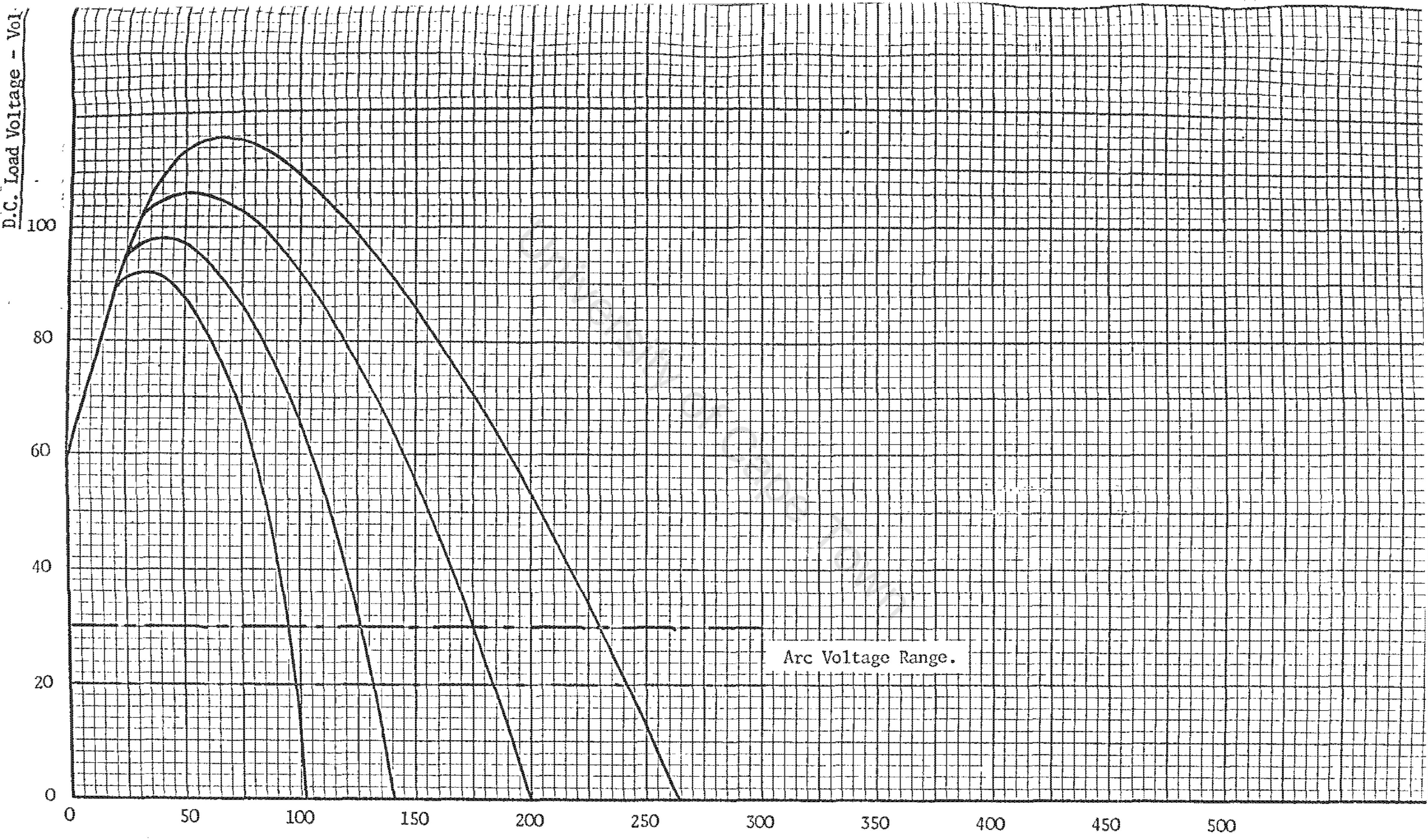
In the case of Fig. 9.2 the C.T. burden resistor RCT is set high at approximately 25 ohms and the total field current adjusted by RA to give load curves of increasing field current. In Fig. 9.3 RCT is set low at approximately 5 ohms and RA adjusted to give load curves of increasing field current. In Fig. 9.4, RA is set at zero resistance and RCT is adjusted from zero to approximately 5 ohms to give load curves of increasing field current.

From the load characteristics it can be seen that the high value of RCT in Fig. 9.2 produces a large proportion of feedback current in the field excitation to give the curves a steep slope and high voltage peaks at low load currents. The steep slope is desirable for constant current operation at welding voltages between 20 and 30 but the high voltage peaks are a disadvantage in this case.

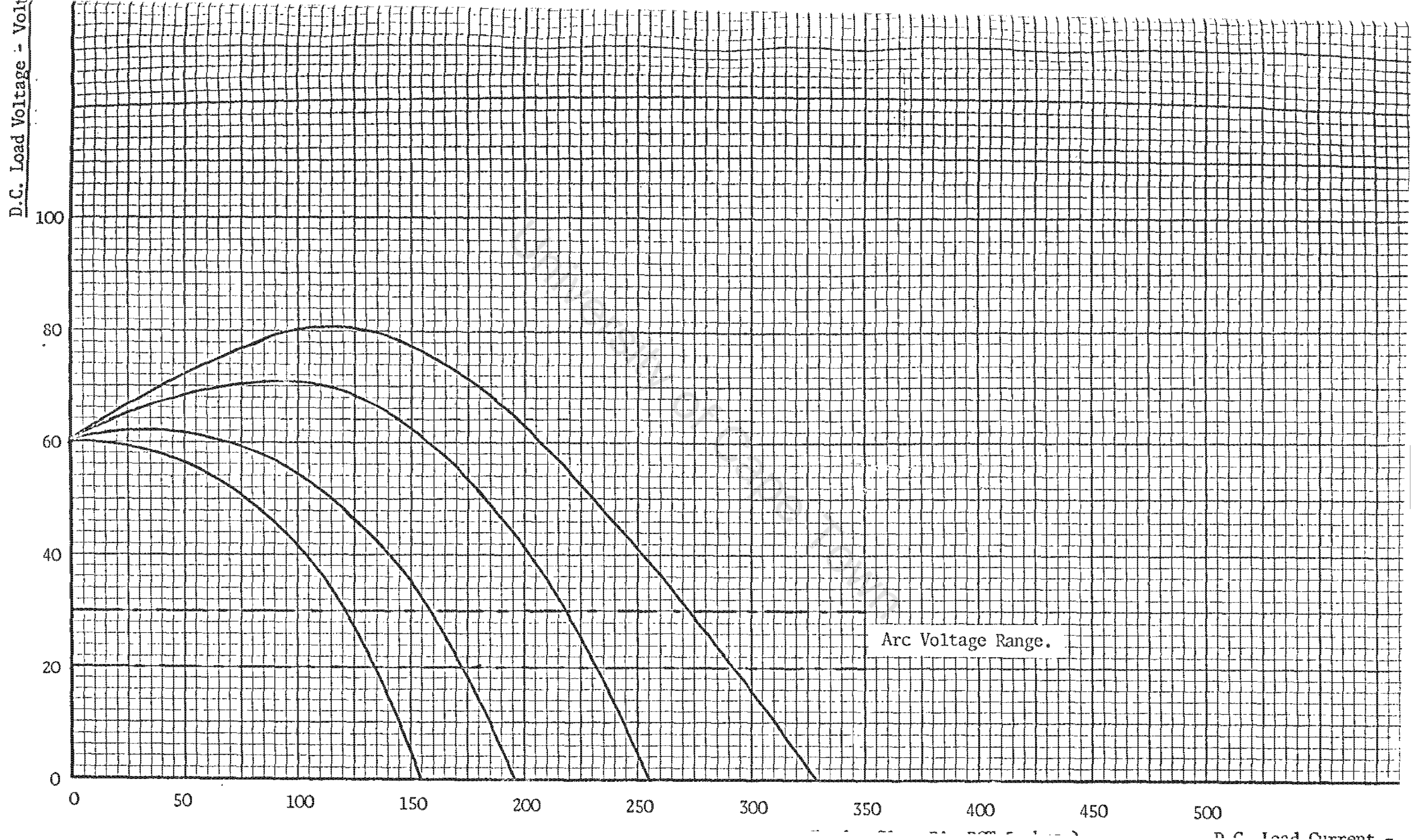
For the lower values of RCT in Fig. 9.3 and Fig. 9.4 the high voltage peaks have been reduced to an acceptable level but the slope of the load curves has also been reduced to give increased current variation between welding voltages of 20-30 volts.

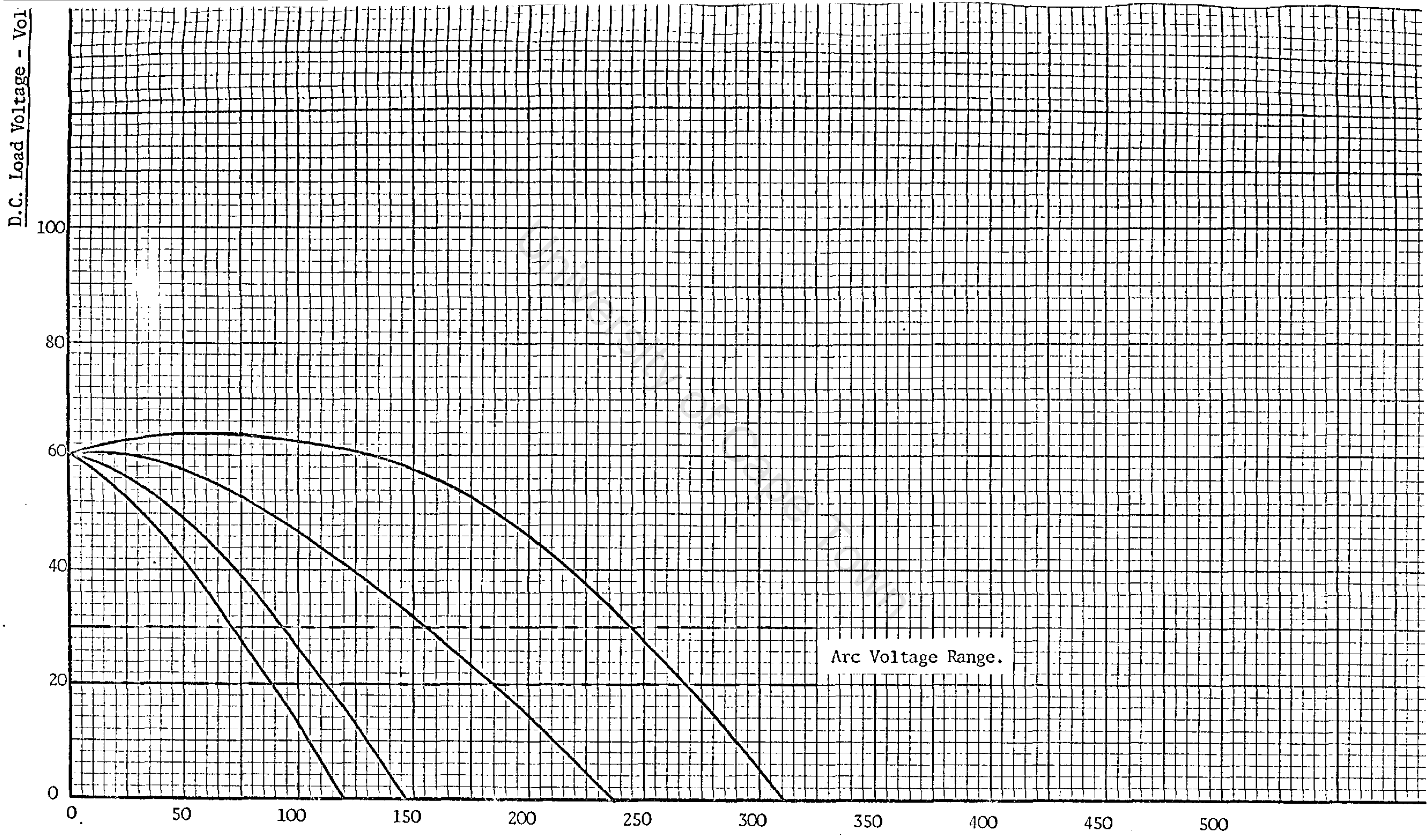
For the curves of Fig. 9.4 with excitation variation by means of RCT only, the open circuit voltage remains constant for each load curve of increasing field current. This is not the case however in Figs. 9.2 and 9.3 where the field excitation is also controlled by varying RA.

As/...



D.C. Load Voltage - Vol
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
450
500
Arc Voltage Range.


D.C. Load Voltage - Volt
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
450
500
Arc Voltage Range.
D.C. Load Current -


D.C. Load Voltage - Vol
100
80
60
40
20
0
0.
50
100
150
200
250
300
350
400
450
500
Arc Voltage Range.

As the open circuit voltage changes with a change in RA, it is necessary to adjust RB each time to maintain the open circuit voltage at a constant level. This is a further disadvantage in the control of the welder, so the characteristics obtained in Fig. 9.4 with independent voltage and current control are the most suitable, although not being true constant current characteristics.

9.4 WELDING CHARACTERISTICS

The dynamic welding characteristics obtained with the welder using the control circuit described in the previous section are given here, together with the transient response characteristics of the machine.

9.4.1 MACHINE'S TRANSIENT RESPONSE

In order to predict the performance of the welder in terms of weldability and arc stability, the transient characteristics of the machine to short and open circuit conditions are investigated.

For these tests the inductance in the output circuit of the D.C. welding supply is varied to give an indication of the value to be used for the trial welding tests.

There are two D.C. chokes available for use as inductance in the output circuit. They have a measured inductance of -

(a) Choke 1. Inductance of 0.6 mH at 50 Hz

(b) Choke 2. Inductance of 1.5 mH at 50 Hz.

An open circuit voltage of 65 volts was used for the tests and the current limited to 120 amps on

short/...

short circuit.

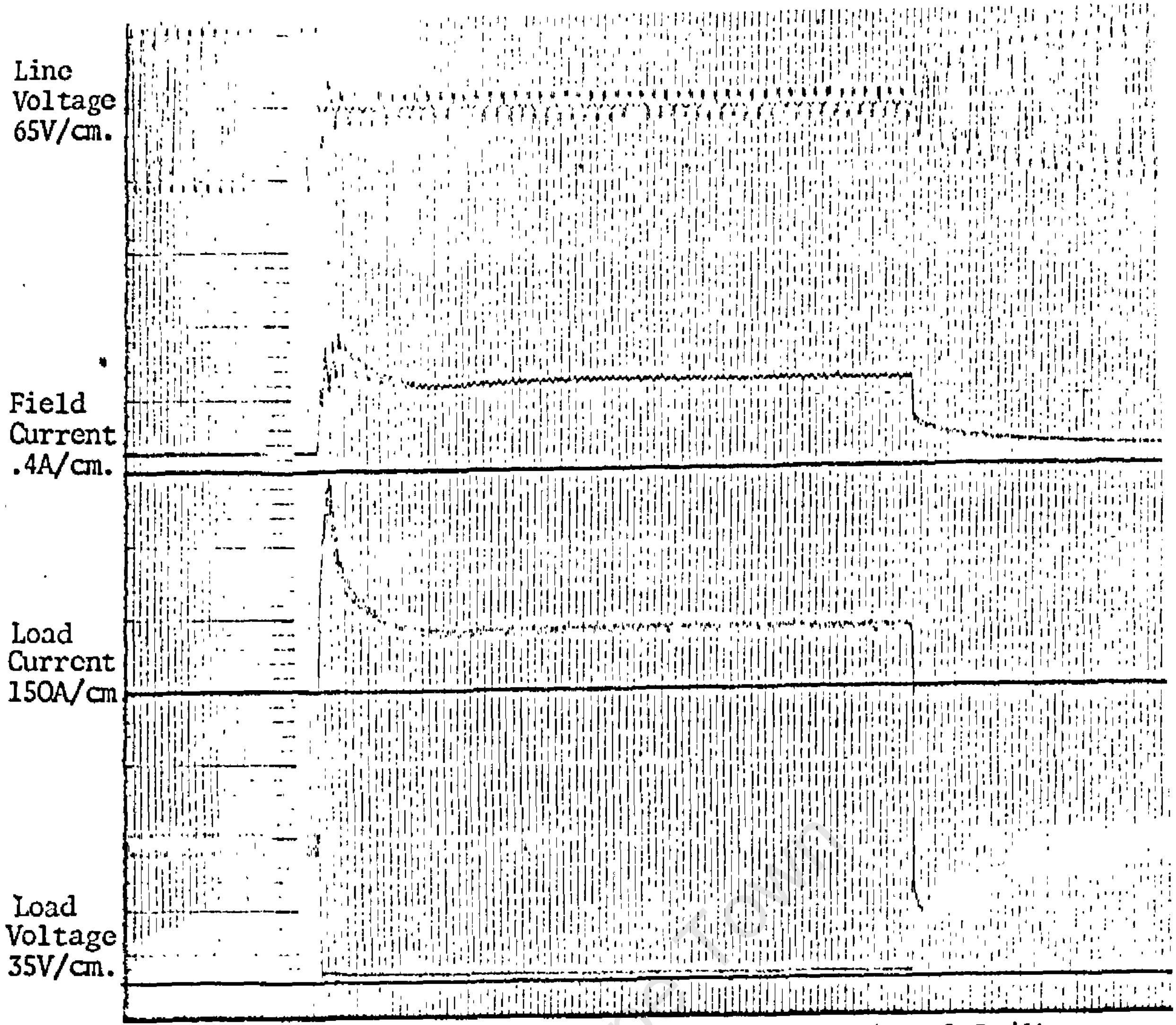
Rec. 9.1 shows the transient response of the machine to a short and open circuit with Choke 1 in the output. The current rises to almost 4 times the steady state value in approximately 12 mS and decay is rapid with a time constant of approximately 50 mS.

Rec. 9.2 shows a similar response but with Choke 1 plus Choke 2 in series giving an effective inductance of 2.1 mH in the output circuit. The current rise is reduced to 3 times steady state value and the peak is reached after 30 mS. The decay is less rapid with a time constant of approximately 80 mS. The voltage rise at open circuit is similar to that of Rec. 9.1 with a "reserve" voltage of 30 volts. The transient peak rise is approximately 25 volts greater than in Rec. 9.1 but the recovery voltage rises to the open circuit value with time constant of approximately 180 mS in both cases.

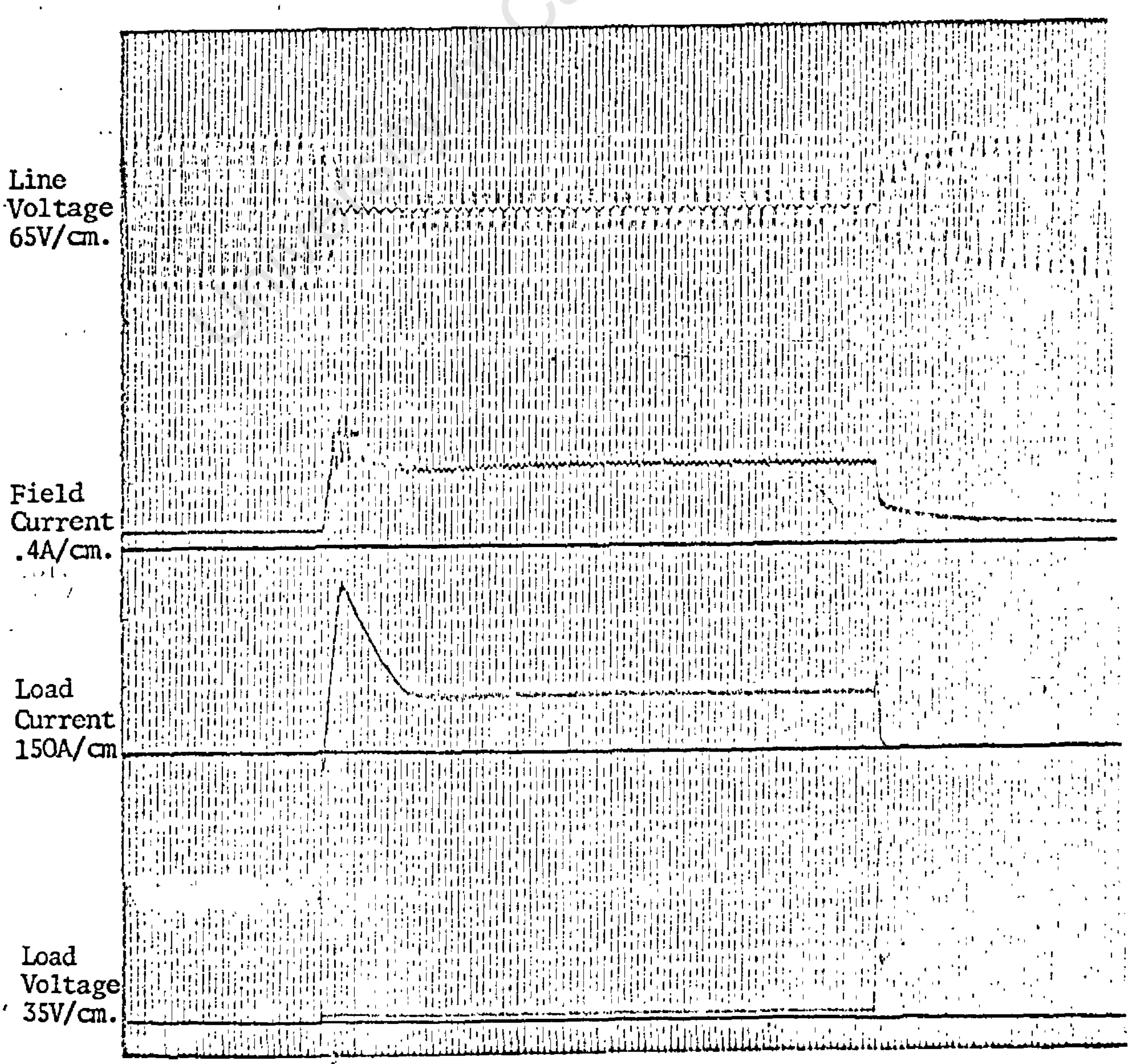
There are also small sub-transient changes in current at short and open circuit for Rec. 9.2 which show the effect of the stored energy in the inductance. A negative transient at short circuit indicates current reversal to store the energy and a positive transient at open circuit indicates the increase in current with the release of the stored energy.

Rec. 9.3 gives the response when Choke 2 alone is connected in the output circuit. As can be

expected/...


Line Voltage 65V/cm.
Field Current .4A/cm.
Load Current 150A/cm
Load Voltage 35V/cm.
Time-10mS./div.

Rec. 9.1


Line Voltage 65V/cm.
Field Current .4A/cm.
Load Current 150A/cm
Load Voltage 35V/cm.
Time-10mS./div.

Rec. 9.2

expected the response times and current peaks lie between those obtained for Recs. 9.1 and 9.2. There are no sub-transient changes in current at short and open circuit in this case but the inductance of Choke 2 does decrease the current peak and lengthen current decay with respec to Rec. 9.1.

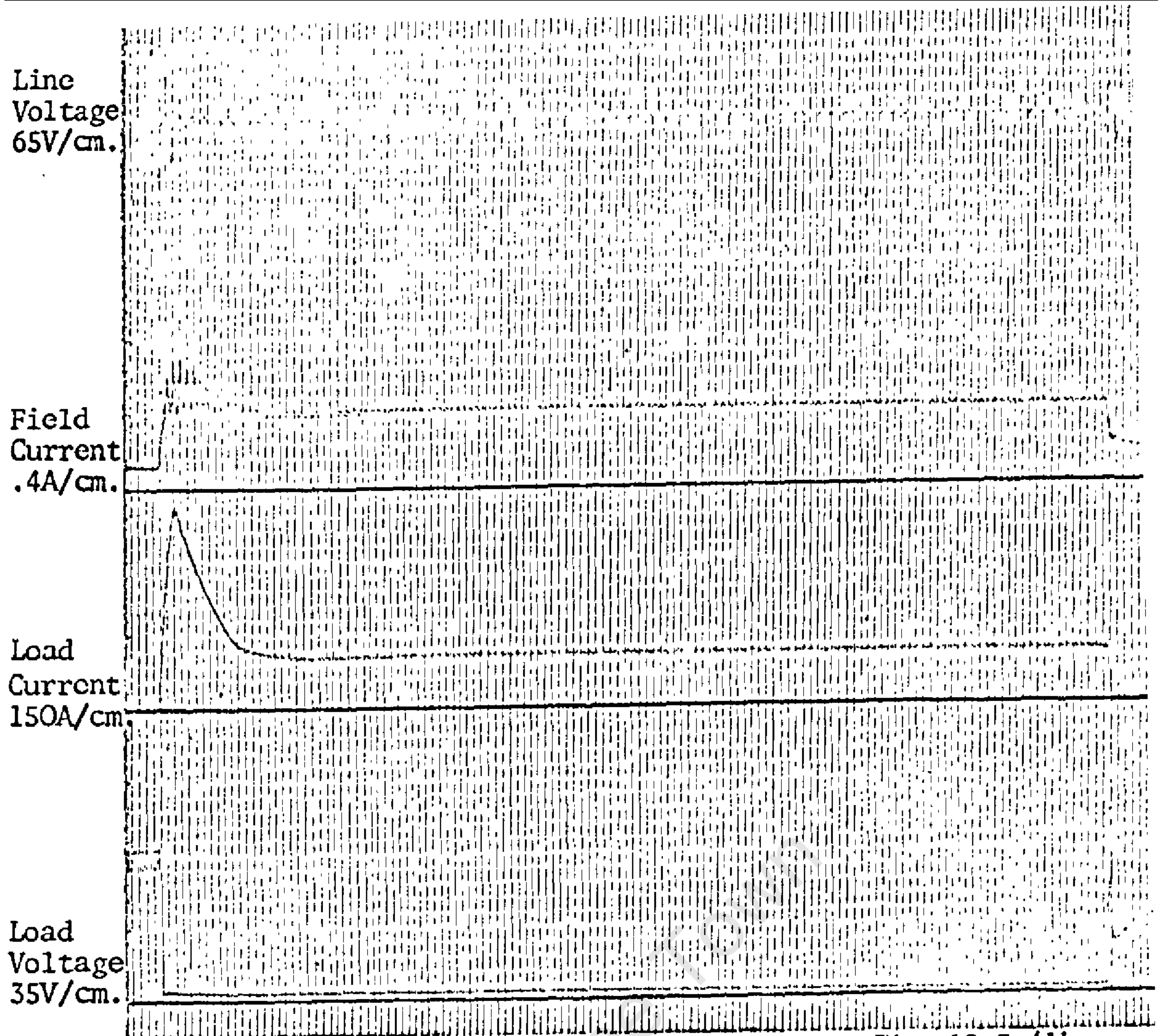
As the current rating of Choke 2 is approximately 200 amps and that of Choke 1 only 100 amps it was decided to use Choke 2 only in the output circuit of the welder for determining the weld characteristics.

9.4.2 WELD CHARACTERISTICS

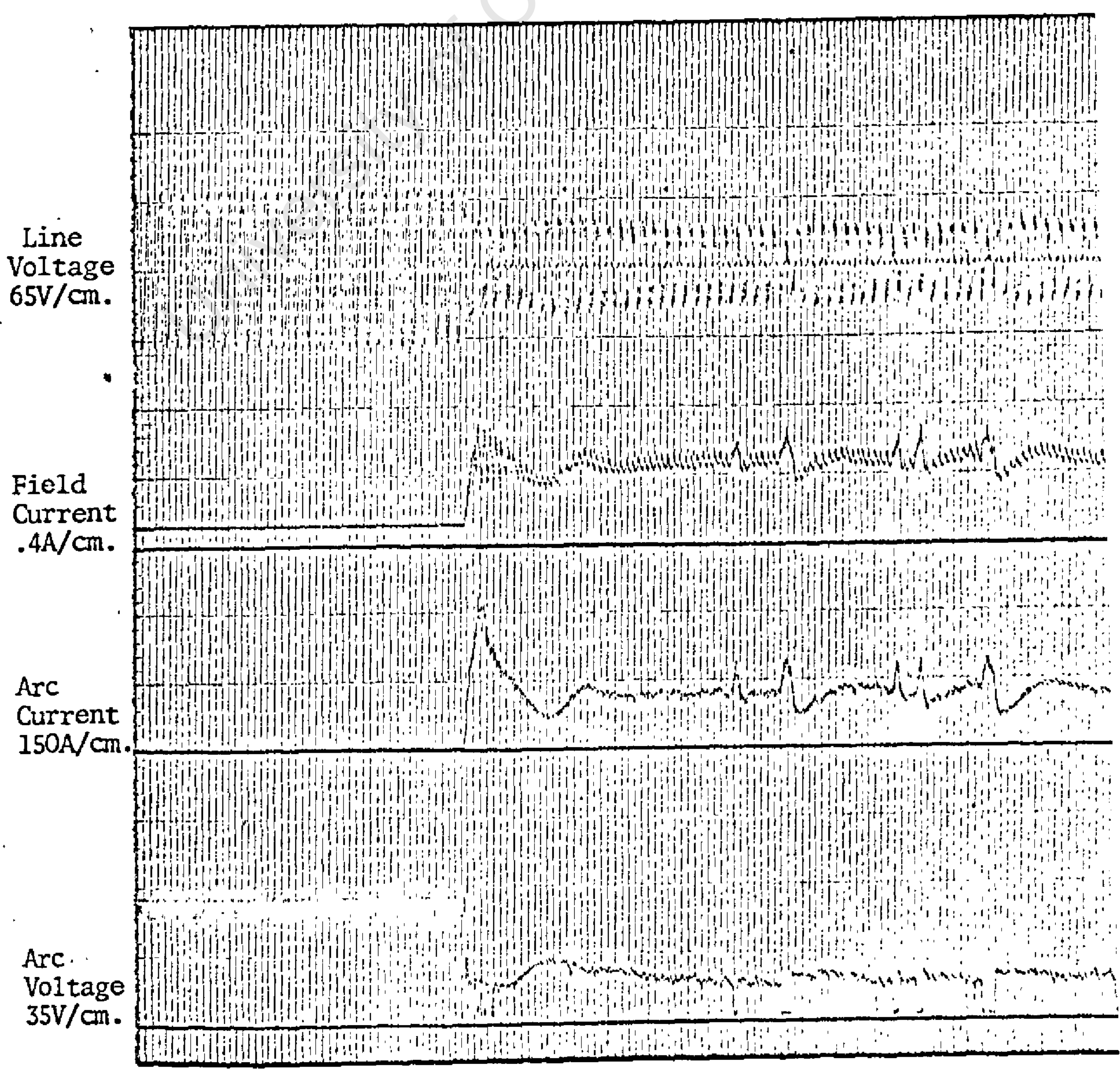
The initial trial welds with the current feedback circuit and using Choke 2 in the output proved satisfactory and the weldability and arc stability were quite acceptable.

Rec. 9.4 shows current and voltage waveforms before and after striking the arc including a short interval of straight welding. Open circuit voltage is 60 volts and the average welding current is 120 amps. Although the initial arc strike is not a complete short circuit the current transient obtained resembles closely that obtained for Rec. 9.3. The increase in field excitation current due to the positive current feedback is easily seen from the field current waveform whose transient characteristics follow those of the arc current very closely. Current overshoot and undershoot are still present but the undershoot is not excessive and does not approach the zero line even after a long arc short of 20 mS.

Rec./...


Line Voltage 65V/cm.
Field Current .4A/cm.
Load Current 150A/cm
Load Voltage 35V/cm.
Time-10mS./div.

Rec. 9.3


Line Voltage 65V/cm.
Field Current .4A/cm.
Arc Current 150A/cm.
Arc Voltage 35V/cm.
Time-10mS./div.

Rec .9.4.

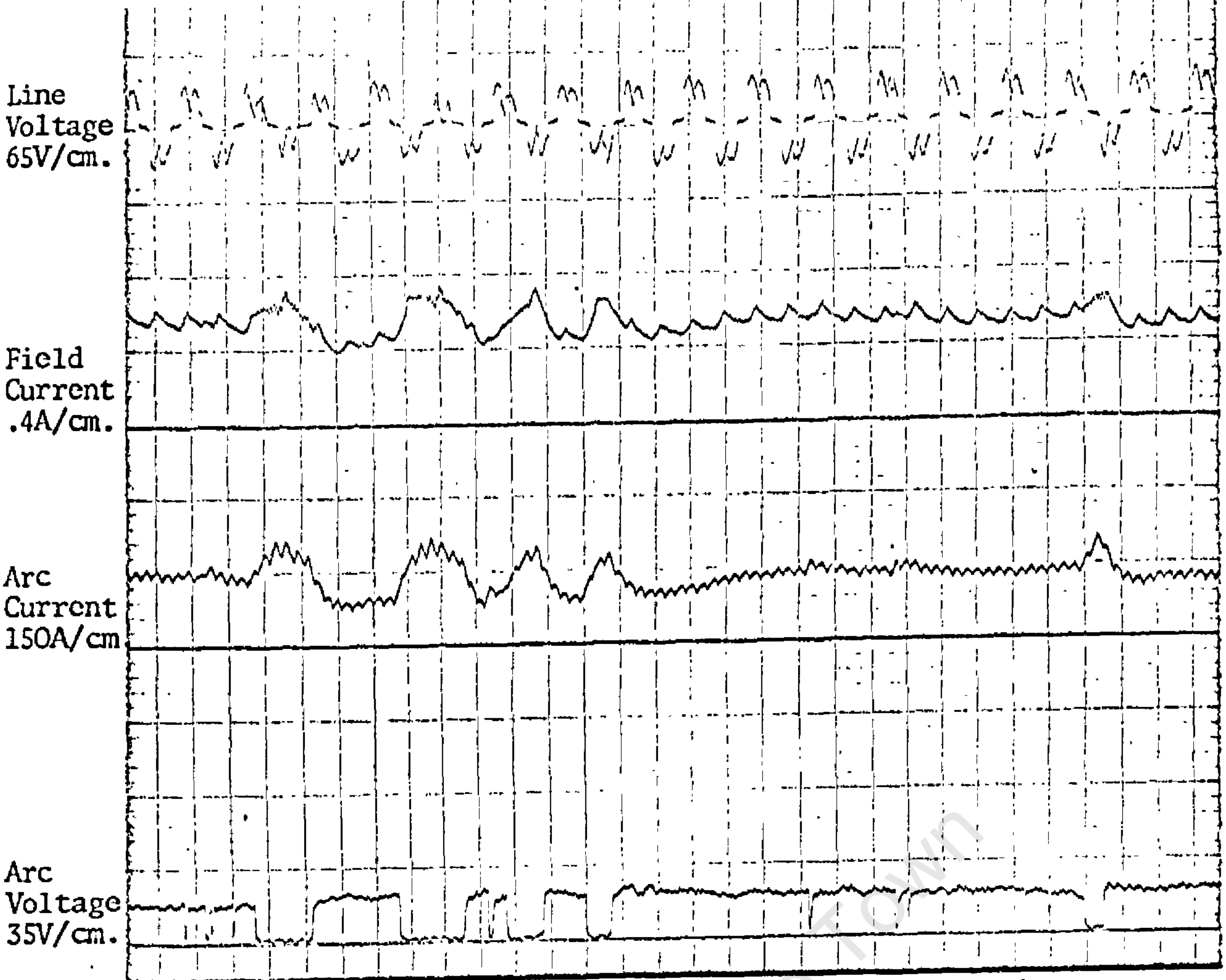
Rec. 9.5 shows typical waveforms on an expanded time scale and the arc shorting times and current variations can easily be measured from the recording. The current changes are sufficiently damped to prevent instability and extinction.

Rec. 9.6 shows current and voltage waveforms obtained when welding with a special type of electrode. The electrode used in this case is a 10 guage Bronzend rod for bronze and other alloy metals. The waveforms differ considerably from those obtained with mild steel electrodes owing to the absence of arc short circuits and the corresponding overshoots and undershoots in the current waveforms. Although it would appear that this type of electrode gives very stable arc characteristics, the flow of metal from rod to the work is difficult to control and only experienced operators should attempt this kind of welding.

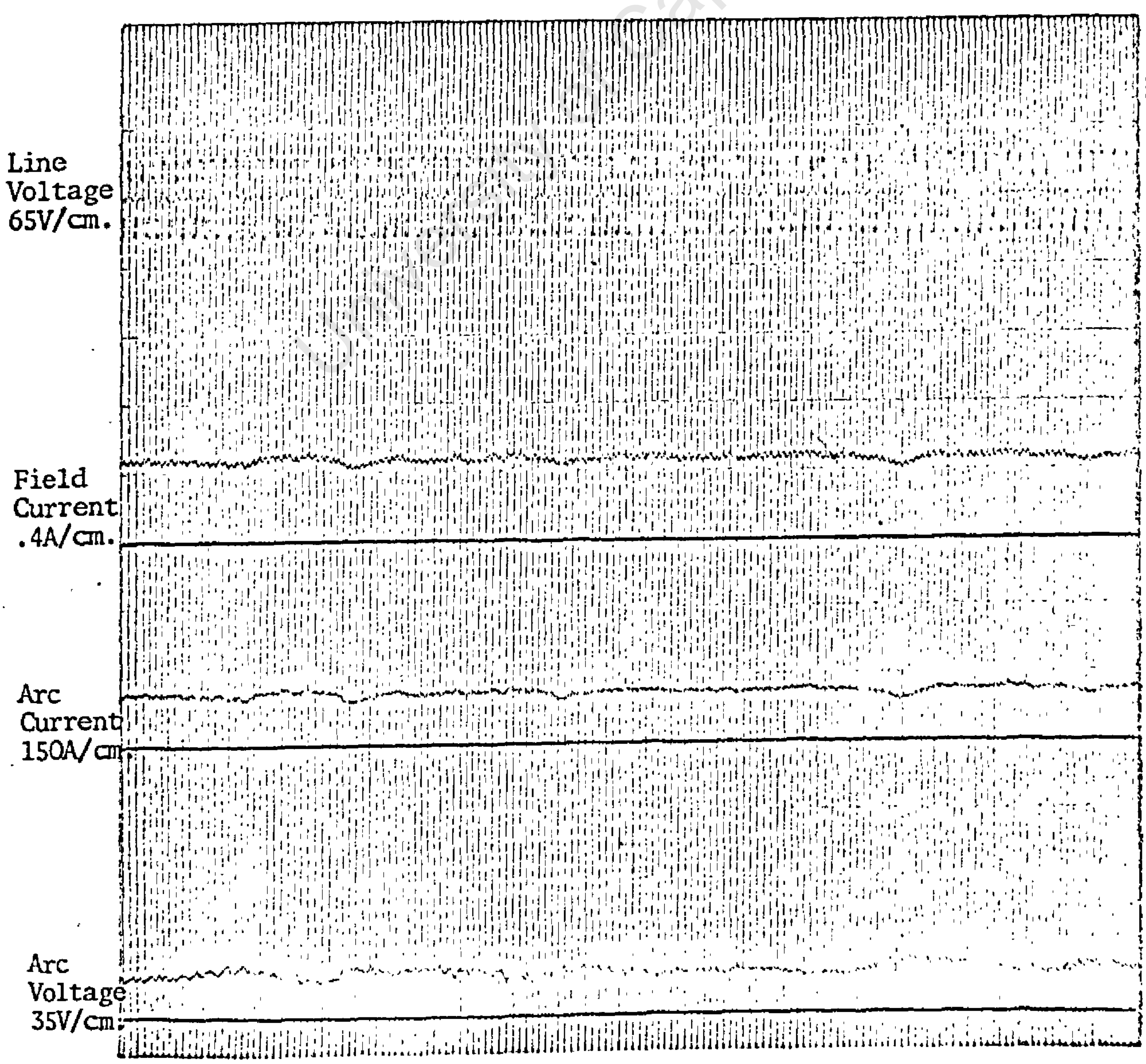
Rec. 9.7 shows the waveforms obtained when welding with a heavily coated iron arc shield and gives increased metal deposition with a longer arc length as shown by the increased arc voltage waveform. The increased arc length also minimises the frequency of arc shorts and produces a very stable arc with easy control of metal deposition.

Rec. 9.8 (a) and (b) illustrates the difference between current and voltage waveforms when the polarity of the welding electrode is changed. In most cases of D.C. arc welding "straight" polarity with the electrode negative and the work positive is used. One reason for this is that approximately

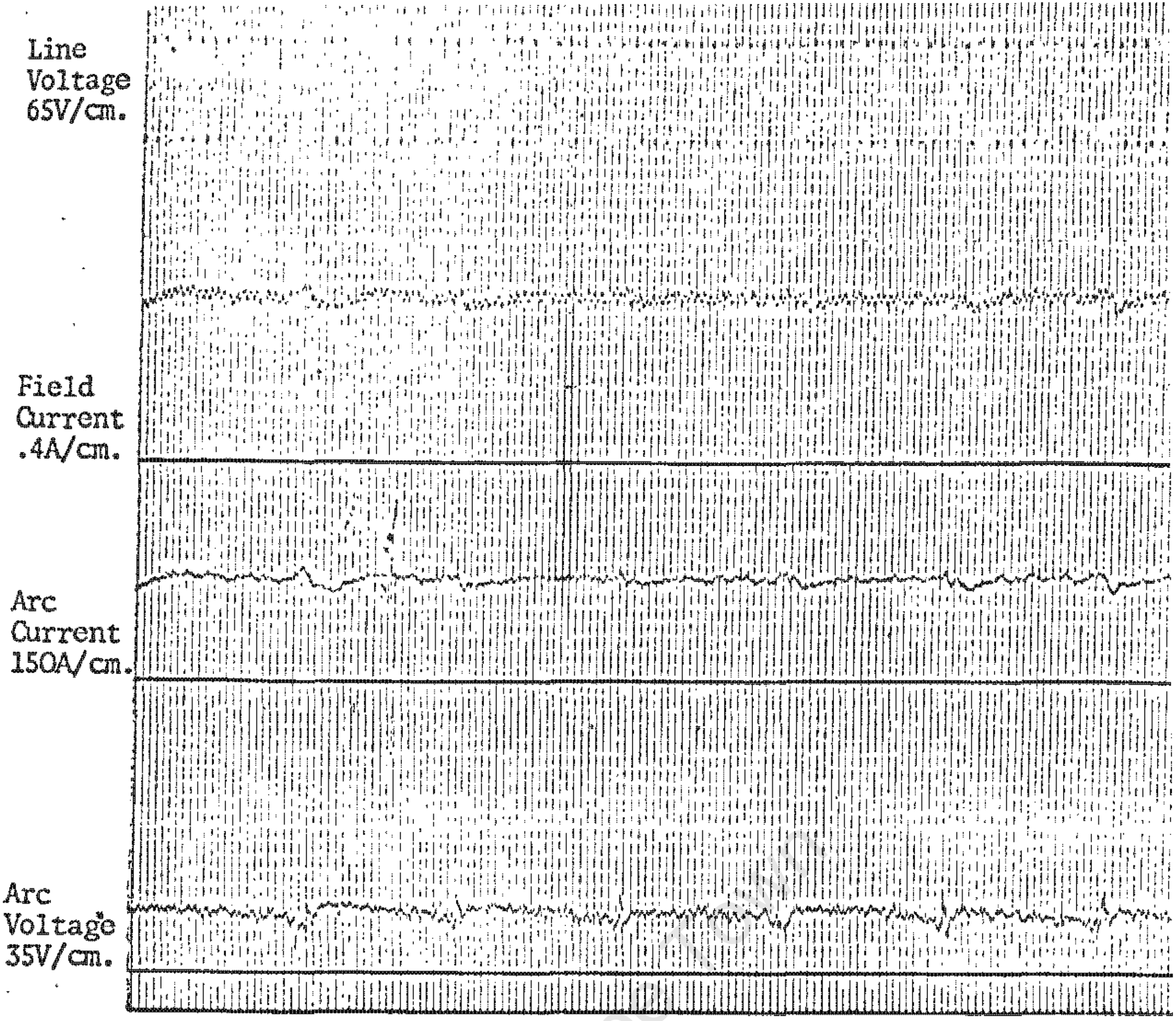
two-thirds/...



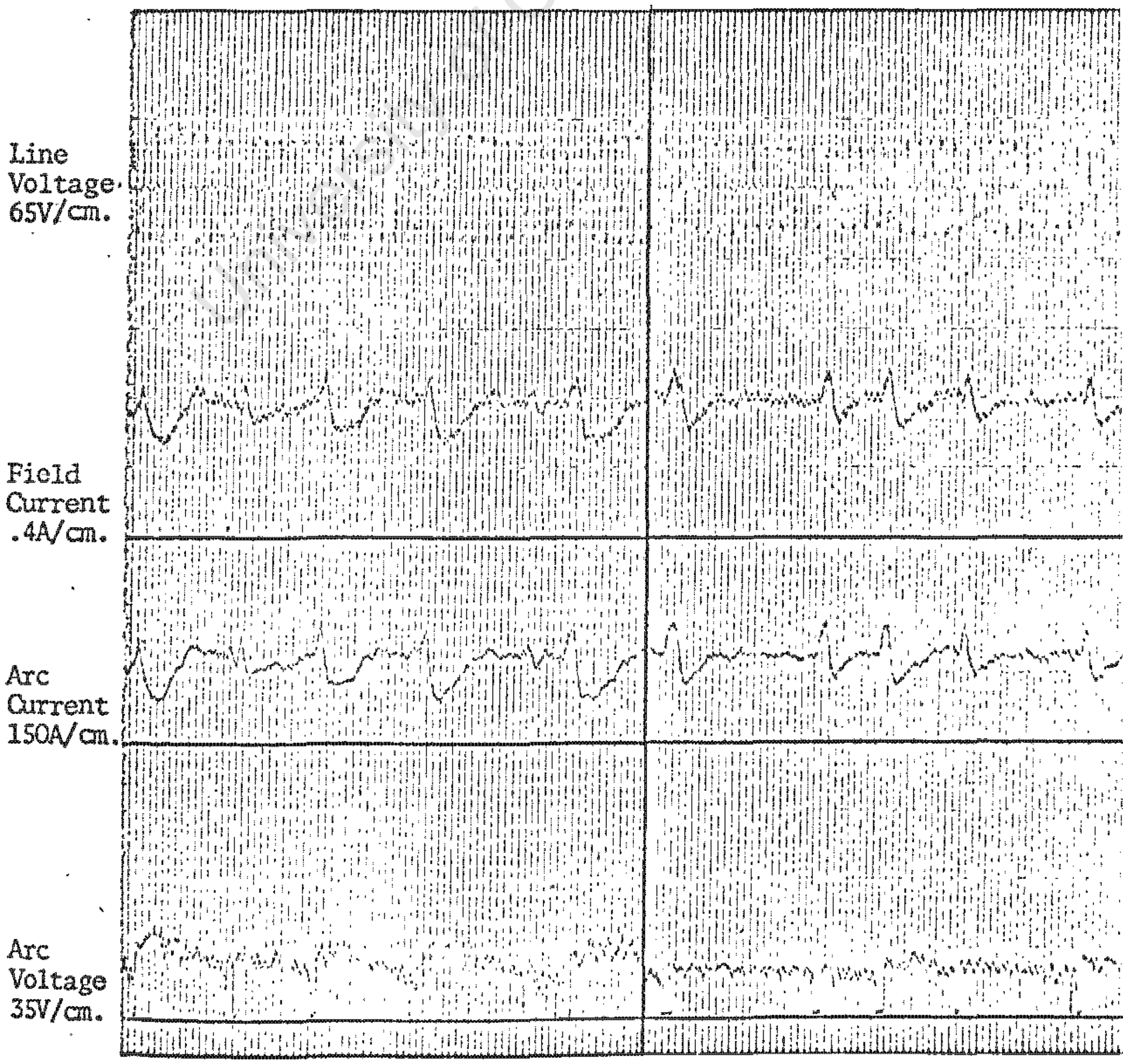
Rec. 9.5 Time-10mS./div.



Rec. 9.6. Time-10mS./div.



Rec. 9.7



Rec. 9.8 a & b.

two-thirds of the heat generated by the arc appears at the positive terminal so it is usually best to heat the work more than the rod. Occasionally it is necessary to change the polarity of the weld and make the electrode positive and the work negative. This is termed "reversed" polarity and is used sometimes when welding alloys and using special rods.

Rec. 9.8(a) gives waveforms obtained when using "straight" polarity to weld with a special cellulose coated deep-penetrating rod. There is marked current undershoot and a rise in arc voltage after an arc short occurs showing possible arc instability. Rec. 9.8(b) gives waveforms obtained with the same rod but using "reversed" polarity and indicates from the current and voltage variations that the arc stability has been considerably improved. This recording now closely resembles that of Rec. 9.4 which has satisfactory arc stability; so for this special rod it is best to weld with "reversed" polarity.

10. CHARACTERISTICS OF THE NEW MACHINE

As shown in the previous section, the A.C. brushless alternator can readily be converted for use as a D.C. welding generator.

The alternator used for these tests, the 'Markon' type SM is however from a discontinued range of machines and has been superceded by the 'Markon' type B range. There are slight differences in the design of the new B range of alternators incorporating the following advantages over the previous SM range.

(a) All stator winding connections are brough out to a common terminal board thus enabling easy reconnection of any winding arrangement.

(b) The rotating diode assembly on the shaft is situated at the rear end of the machine giving easy access for checking and replacing faulty diodes.

(c) The Automatic Voltage Regulator unit is not encapsulated but fitted to a printed circuit board and all electronic components are externally mounted to provide for ease of testing and replacement if necessary.

In order to determine the performance of an alternator from the new B range, various preliminary tests are carried out on the machine.

The 'Markon' B range alternator selected has the same rating as the type SM range already described, namely 31.25 KVA at 50 Hz and 37.5 KVA at 60 Hz.

For 60 Hz operation at 1800 R.p.m. and nominal output voltage of 130 volts for parallel-delta connection:

$$\text{Line current} = \frac{37.5}{\sqrt{3} \times 130} \times 10^3$$

$$= 164 \text{ amps as before.}$$

10.1/...

10.1 STEADY STATE CHARACTERISTICS

10.1.1 OPEN & SHORT CIRCUIT CHARACTERISTICS

The tests to determine these characteristics are carried out as described in Sections 3.1 and 3.2. The circuit diagram is that given in Figs. 3.1, 3.2. and 3.3.

The results obtained are shown in the O.C.C. and S.C.C. curves of Fig. 10.1.

10.1.2 ZERO POWER FACTOR LOAD CHARACTERISTIC

As the laboratory reactors have a low current rating of 32 amps at 125 volts it is necessary to reconnect the stator windings in series-star for reduced current output as was necessary in Section 3. The reactors were delta connected and the line currents kept constant at the full load value, while the reactor air gaps were reduced in steps to zero.

The circuit diagram is the same as that of Fig. 3.4 and the results are given in Fig. 10.2 together with the open circuit curve for series-star operation.

10.1.3 CONSTANT OF THE MACHINE

(a) Stator and Field Resistance.

The D.C. resistance of one stator phase winding in parallel-delta connection and the field exciter stator winding are:

Stator winding, R_a = .012 ohms

Field winding, R_f = 16.8 ohms

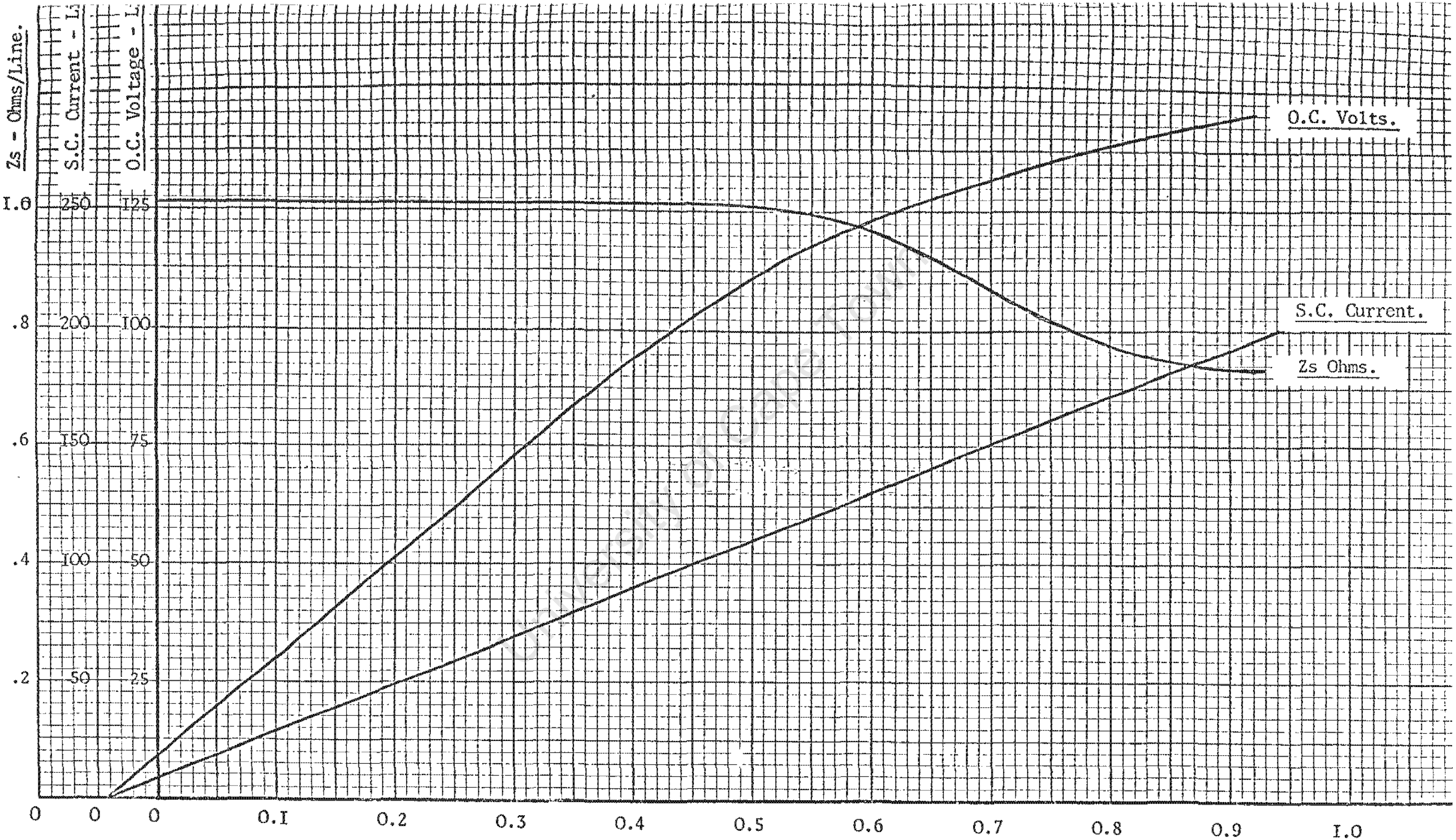


Fig. 10.1 Open, Short Circuit & Zs Characteristics for Parallel-Delta Connection.
(B range Machine)

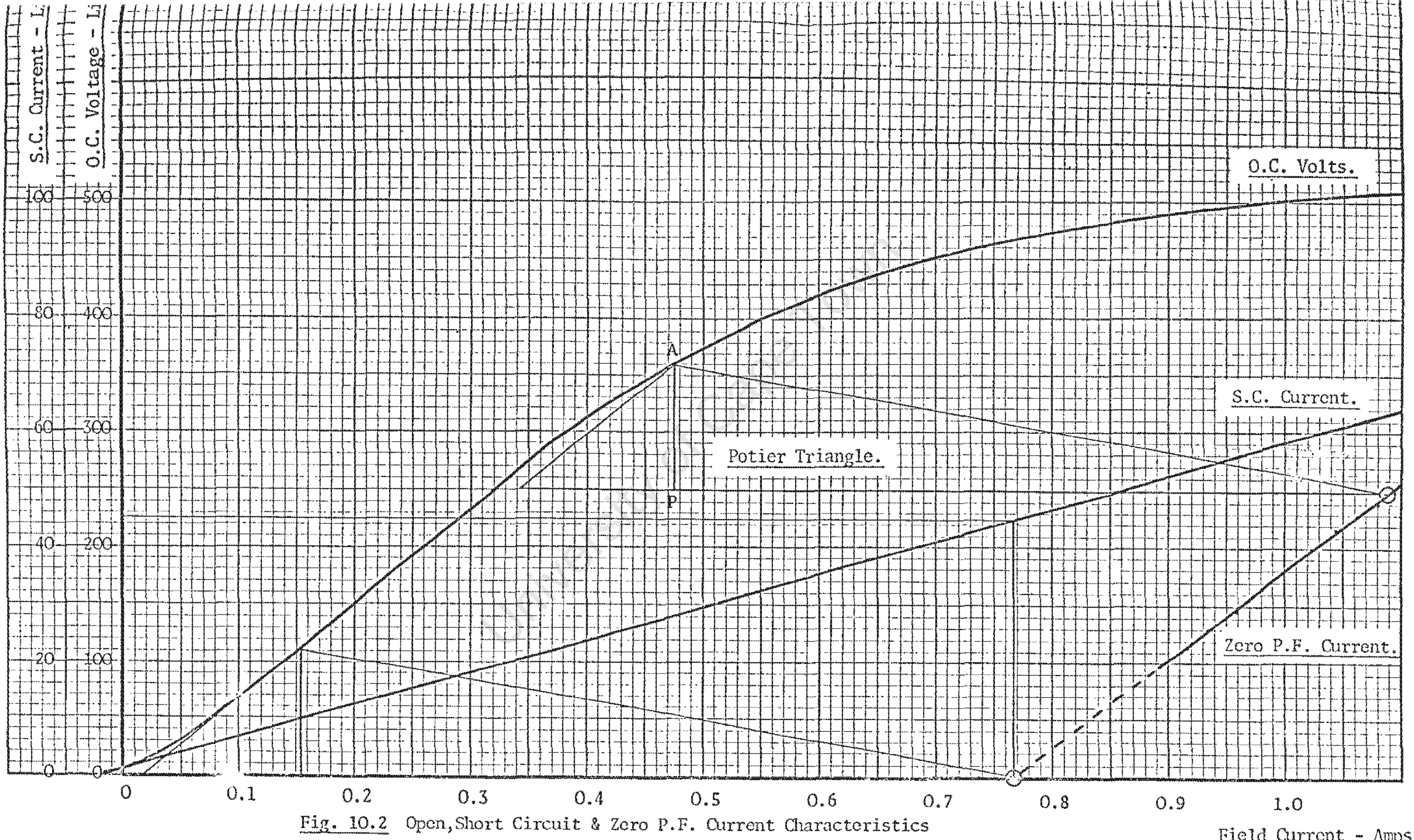


Fig. 10.2 Open, Short Circuit & Zero P.F. Current Characteristics
for Series-Star Connection. (B range Machine)

(b) Stator Inductive Leakage Reactance, Xl.

For the Zero Power Factor test, the constant load current = 45 amps. The Potier triangle is constructed for the point at 250 volts line on the Z.P.F.F.L.C, then:

$Ez = AP = 110$ volts from the triangle

and $Ez = IFL\sqrt{Xl^2 + Ra^2}$

so $63.5 = 45\sqrt{Xl^2 + .012^2}$ per phase

$\therefore Xl^2 = 1.41^2 - .012^2$

$= 1.99$

$\therefore \quad = 1.41$ ohms per phase.

Dividing by 12 for the conversion factor from series-star to parallel-delta connection:

$$Xl = 0.117 \text{ ohms per phase}$$

(c) Synchronous Impedance, Zs

This is determined from the open and short circuit characteristics, as before

$$Zs = \frac{Eo}{Isc}$$

The curve is given in Fig. 10.1 together with the O.C.C. and S.C.C.

To convert values of Zs, given in ohms per line, to ohms per phase the resistance is multiplied by $\sqrt{3}$.

(d) Equivalent Circuit.

The equivalent circuit and corresponding vector diagram is the same as given in

Fig./...

Fig 3.7 but with different circuit values, as given below.

10.1.4 COMPARISON WITH PREVIOUS MACHINE

The constants for the two machines are summarised below.

CONSTANT	SM RANGE	B RANGE
Rf	27.2 ohms	16.8 ohms
Ra	0.02 ohms/ph.	0.012 ohms/ph.
Xl	0.098 ohms/ph.	0.117 ohms/ph.
Zs	1.73-0.81 ohms/ph.	1.77-1.45 ohms/ph.
Xa	1.63 ohms/ph.	1.60 ohms/ph.

From the values given in the table there is a general agreement between the constants of the alternators from the two ranges.

The B range alternator has however a much lower field exciter stator resistance, Rf. This is an advantage as a lower D.C. supply voltage for the field may be used to obtain the same excitation current as for the SM range machine.

The inductive leakage reactance of the machine, Xl, is greater for the B range which is also an advantage, but the important quantity for comparing the machines is however the transient reactance, Xl^1. Unfortunately this was not fully investigated for the previous machine and lack of time prevented a detailed analysis of the constants of the new machine being undertaken. A good comparison can however be made between the transient reactance of the machines by studying the current and voltage waveforms obtained at short and open circuit conditions. These waveforms are given in Section 6 for the old machine and later in this section for the new machine.

A further difference in comparison of the alternators is the marked improvement in the linearity of the open circuit magnetising curve for the B range machine. Saturation occurs at correspondingly higher values of exciter field current indicating that the M.M.F. produced in the B range machine must be less than in the old S.M. machine. This is confirmed by the Open Circuit Characteristics in Figs. 3.8 and 10.1 which show the reduced voltage obtained for the B machine. A difference in output from the exciter rotor windings of the two machines will account for this change in the characteristics and the main field current will thus be less in the case of the new machine. A smaller voltage change for varying exciter field currents will enable a closer control on the output voltage of the 3-phase supply to be maintained.

The values of armature reaction Xa, are almost equal, indicating that the rotor circuits of the two machines are of a similar design.

10.2 TRANSIENT CHARACTERISTICS

The transient response of the machine to short and open circuits is a good method of determining whether the generator will perform satisfactorily as a welder.

The tests were carried out firstly without any inductance in the D.C. output circuit and then secondly with Choke 1 in the output circuit as described in Section 9.4.

10.2.1/...

10.2.1 NO D.C. INDUCTANCE

Rec. 10.1(a) shows the machine's response to a short circuit at the D.C. output terminals without any inductance in the output circuit. The open circuit voltage is 45 volts and the current at short circuit rises to approximately 15 times steady state value within 10 mS. The current decays with a time constant of approximately 50 mS which indicates the relatively long interval before the machine's 'armature' reaction, Xa takes effect.

At open circuit as shown in Rec. 10.1(b), there is a transient current undershoot due to the underdamped system and the low value of Xl^1, the transient reactance of the machine. The recovery voltage has a slow rate of rise with a time constant of more than 150 mS and the initial or 'reserve' recovery voltage is only a few volts.

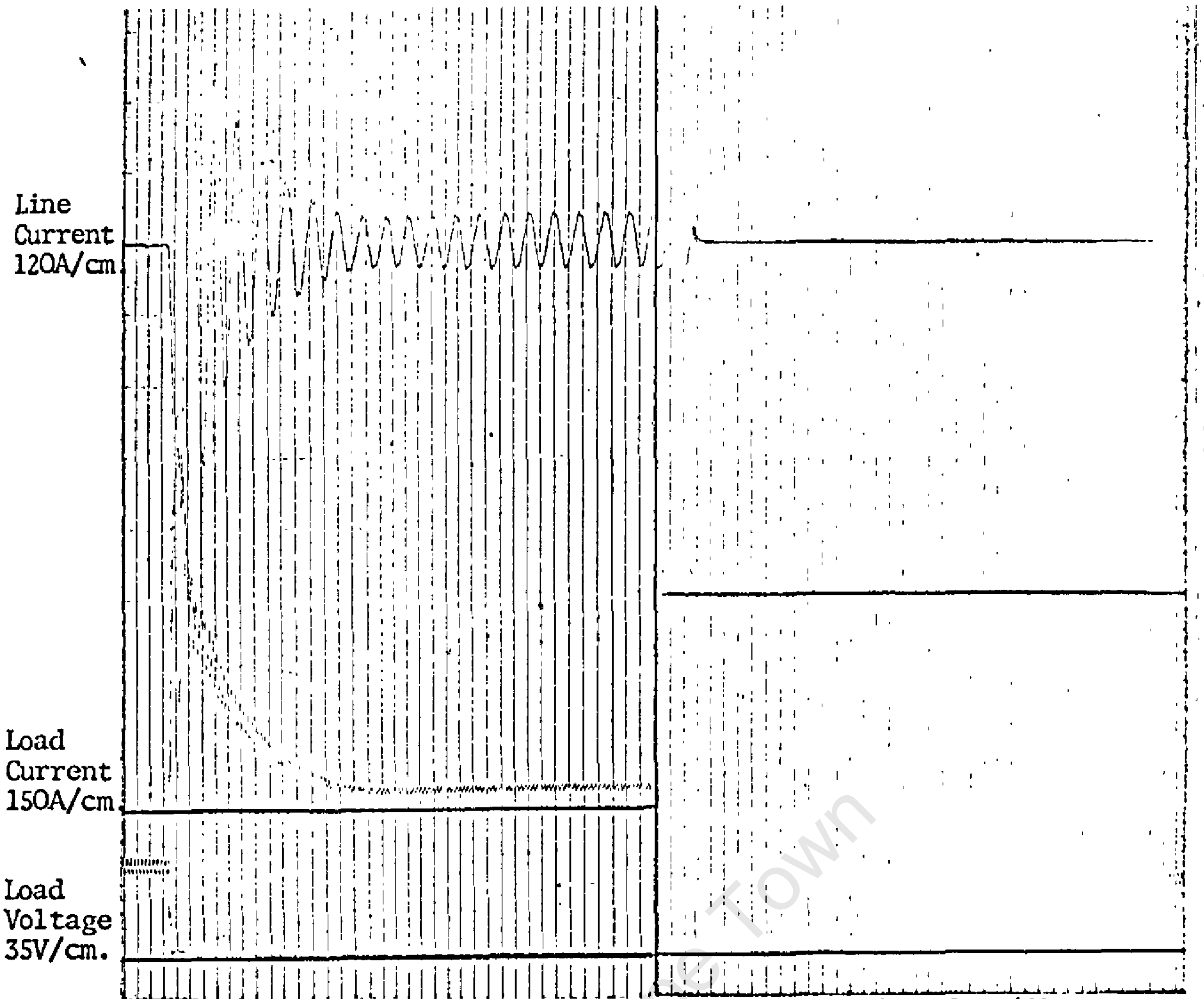
It is thus apparent that the machine on its own is quite unsuitable for welding using the results obtained in Section 9.4 as a comparison, having suitable characteristics for welding. Inductance is therefore necessary in the output circuit.

10.2.2. WITH D.C. INDUCTANCE

In order to limit the current rise and increase the current decay time constant, short and open circuit tests were carried out with Choke 1 in the output circuit.

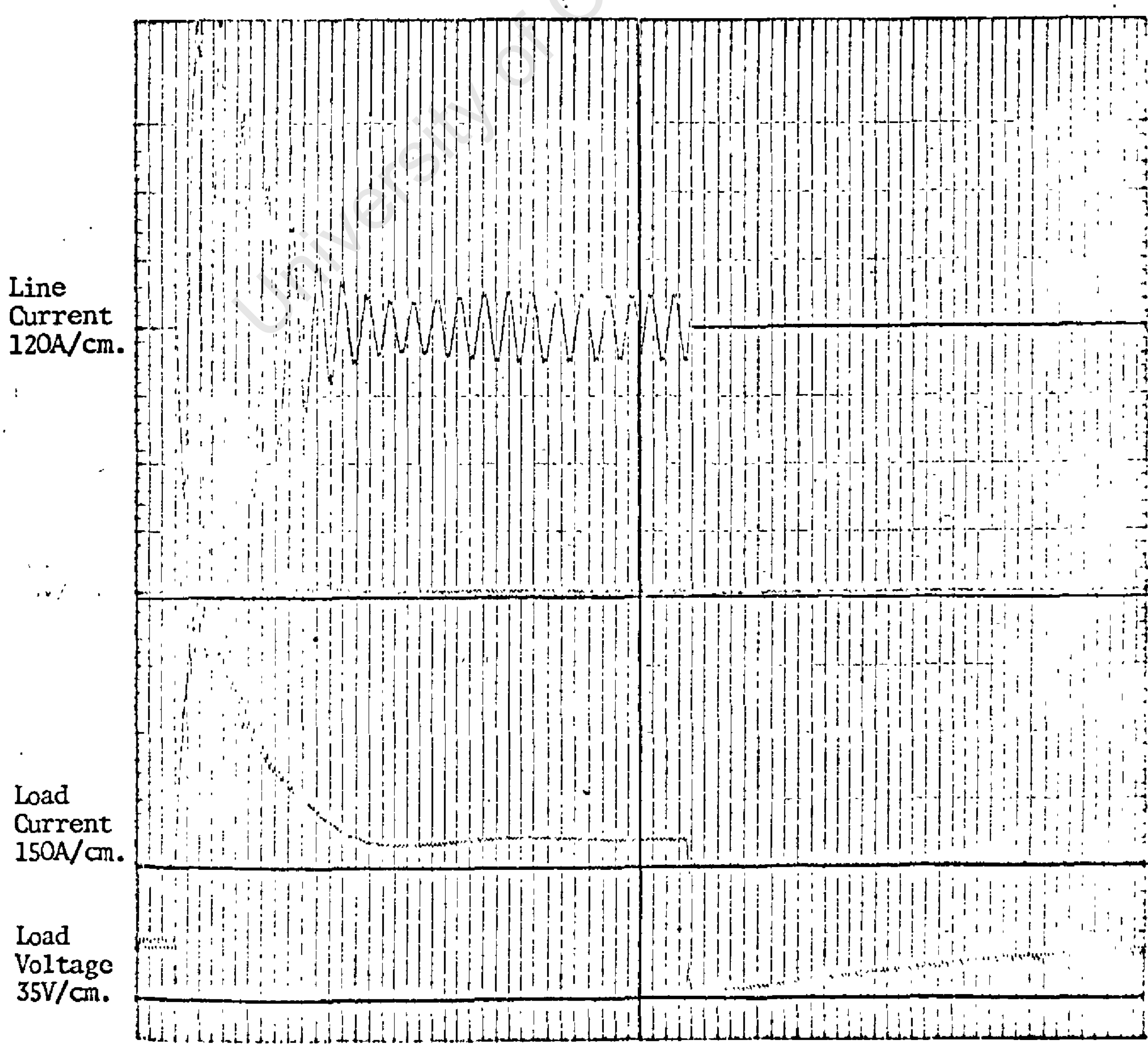
Rec. 10.2(a) shows the response to a short circuit

and/...



Rec. 10.1 a & b.

Time-10mS./div.



Rec. 10.2 a & b.

Time-10mS./div.

and Rec. 10.2(b), the response to the succeeding open circuit. At short circuit the current rises to approximately 10 times final value in 25 mS and decays with a time constant of 60 mS.

Although this is an improvement on the characteristics obtained without the D.C. choke, the current transient is still greater than that obtained in Rec. 9.1 with the previous SM machine.

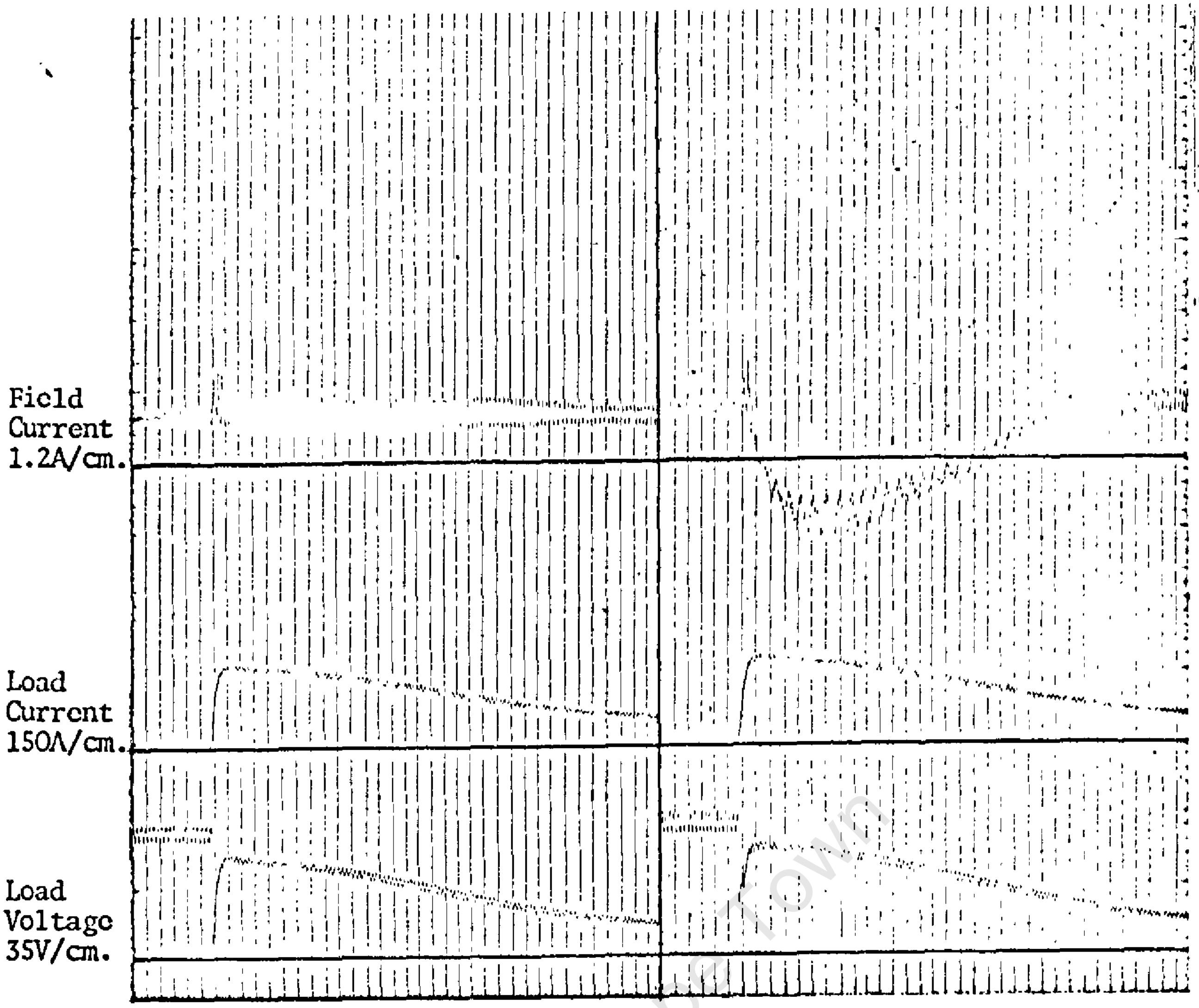
Voltage recovery is much reduced for the B range machine as in Rec. 10.2(b) and thus the differences in alternator constants affect the voltage recovery properties to a great extent. The transient reactance is lower for the B machine and the reduced M.M.F. produces the low voltage recovery on open circuit.

As a comparison, recordings were taken of the machine's response to a resistive arc load. Rec. 10.3(a) shows the response to an on-load short at approximately 50 amps and 60 volts open circuit. The current rises here to 3 times steady state value but the decay has been increased with a time constant of approximately 200 mS.

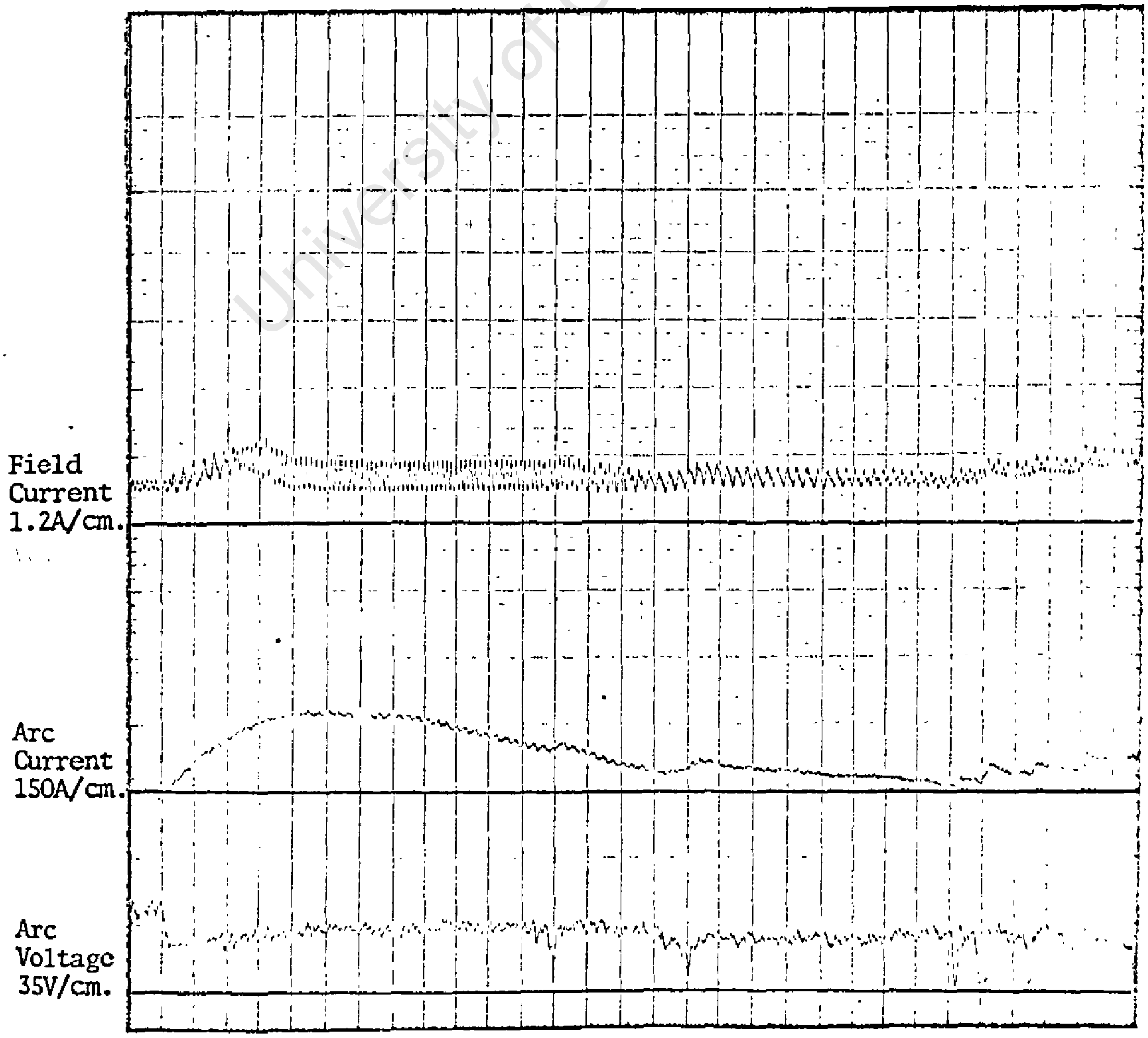
In an attempt to reduce the current rise further, the current feedback circuit was changed to provide negative current feedback for increased output current. Rec. 10.3(b) shows that the negative current in the field excitation circuit failed to have any effect on the output current rise.

10.3 WELDING CHARACTERISTICS

Although the transient characteristics obtained in the previous



Rec. 10.3 a & b.



Rec. 10.4

section are not entirely satisfactory a few tests were carried out on the machine when used as a welder.

Rec. 10.4 shows the waveforms obtained when striking an arc and welding at approximately 45 amps output current. The current rise to about 180 amps when starting a weld is too high, as this excessive current will burn through metal plate of 1/16" or less before the operator has had time to run a proper weld.

This particular characteristic is thus unsuitable and would not be acceptable for industrial use.

As the size of a larger D.C. choke with adequate current rating, would be too big and impractical for use on a transportable welding generator, the possibility of using a 3-phase A.C. reactor in the output of the alternator was considered.

Although there are three separate windings necessary for this type of reactor the lower current ratings on the A.C. side would enable a smaller winding size to be used.

A reactor with an adjustable airgap will enable the optimum inductance to be obtained taking into account the increased saturation for a reduced airgap size.

10.4 CHARACTERISTICS WITH A 3-PHASE REACTOR

A 3-phase reactor with a three limbed core and having an adjustable airgap replaces the D.C. choke in the output circuit of the rectifier.

A description of the reactor together with calculations on the magnetic circuit and the effects of varying the airgap are given in Section 12.3.

The/...

The reactor is placed in circuit in the output from the alternator before the bridge rectifier as shown in Fig. 10.3. Tests were carried out using the control circuit described in Section 9 and the transient characteristics of the system were obtained as in Section 10.2.

10.4.1 TRANSIENT CHARACTERISTICS

Rec. 10.5(a) and (b) shows the machine's response to a short and open circuit at 50 volts and approximately 50 amps steady state load current, with a reactor airgap of 1/8". Here the current rises to a peak of approximately 3.5 times steady value but the average value of the initial under-damped oscillations is only twice the steady state value and the decay is rapid with a time constant of approximately 20 mS.

The recovery voltage at open circuit is 32 volts with a transient peak of 55 volts thus indicating the machine's response to an open circuit is satisfactory for welding requirements.

As a comparison, similar responses are given in Rec. 10.6(a) and (b) for a short and open circuit at 65 volts and 150 amps steady load current. The current rise has an average value equal to the steady value and decreases initially before regaining its final steady value. At open circuit the voltage recovers to normal open circuit voltage in under 10 mS. but with a transient peak of almost twice this value. The current decay at open circuit takes almost 10 mS to fall to zero indicating the effect of the increased inductance in the

circuit/...

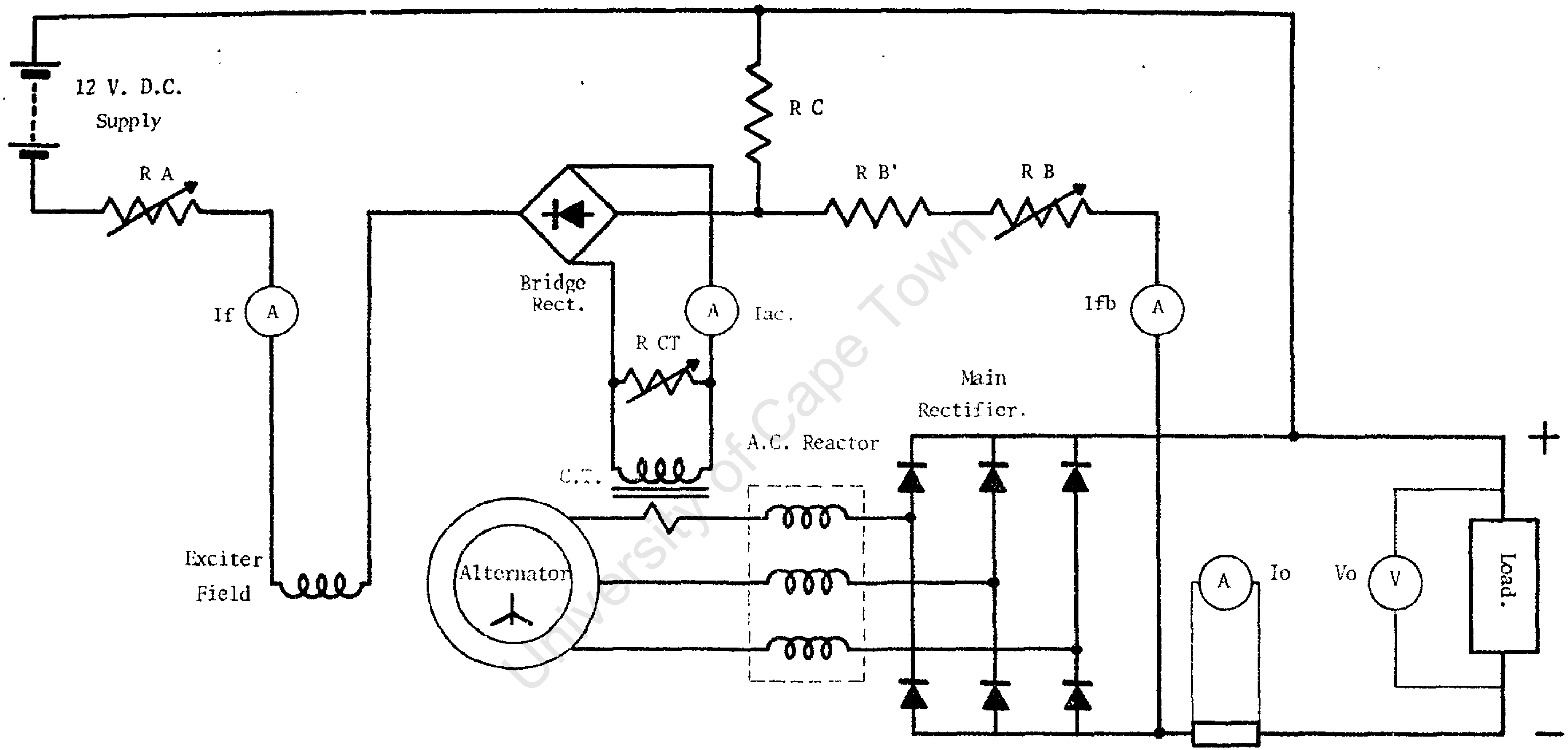
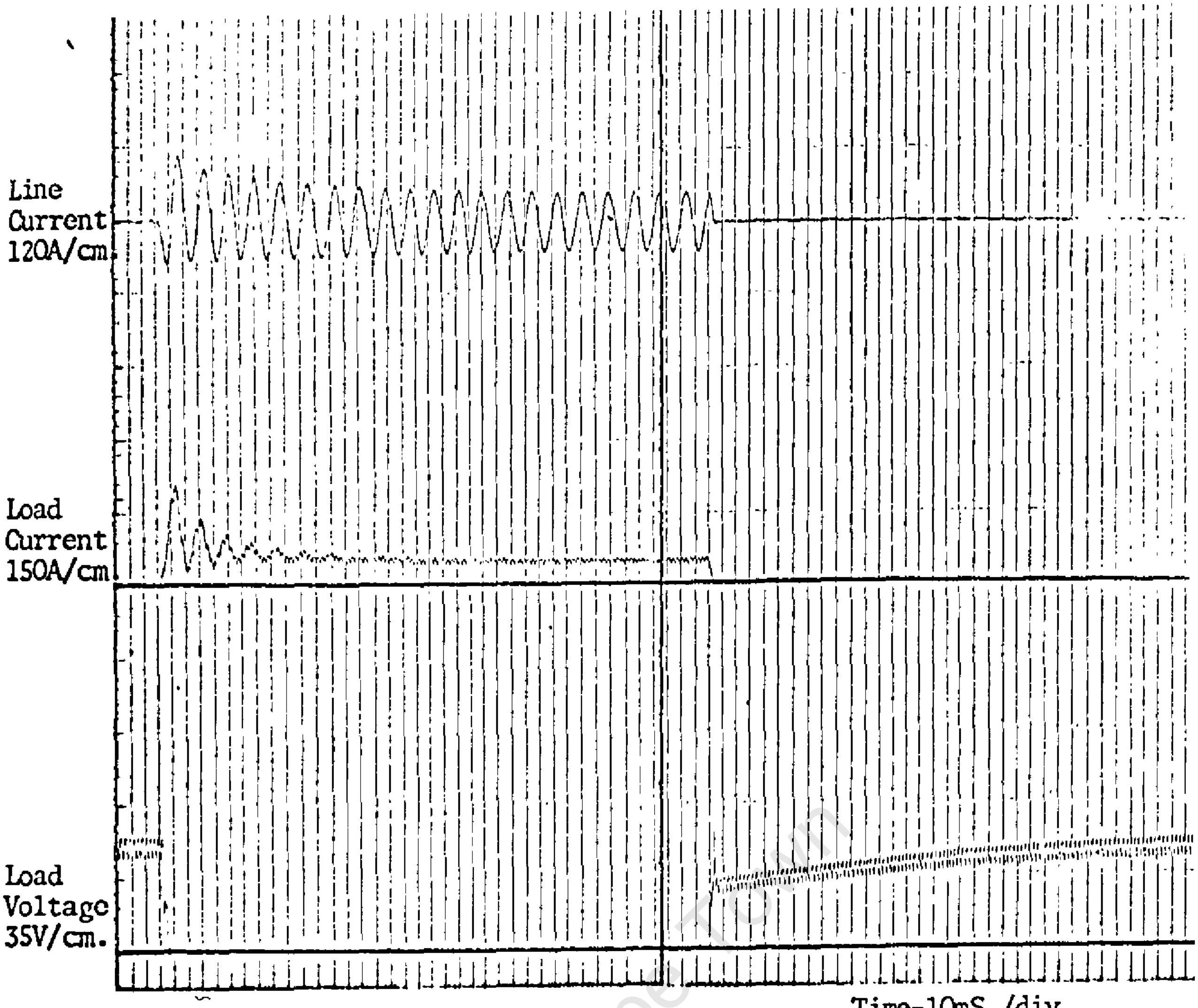
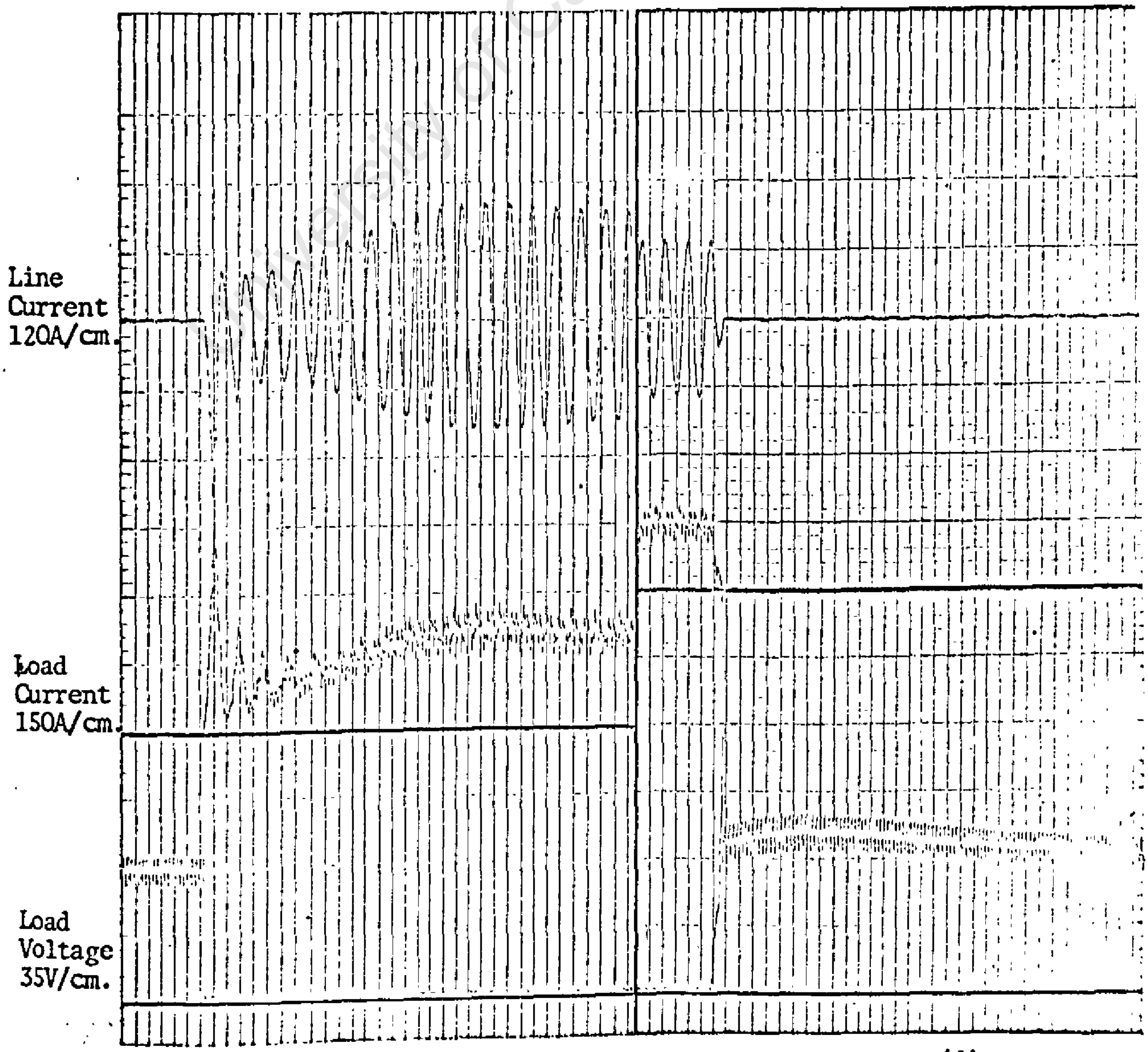


Fig. 10.3 Circuit Diagram with 3-Phase A.C. Reactor.



Rec. 10.5 a & b.



Rec. 10.6 a & b.

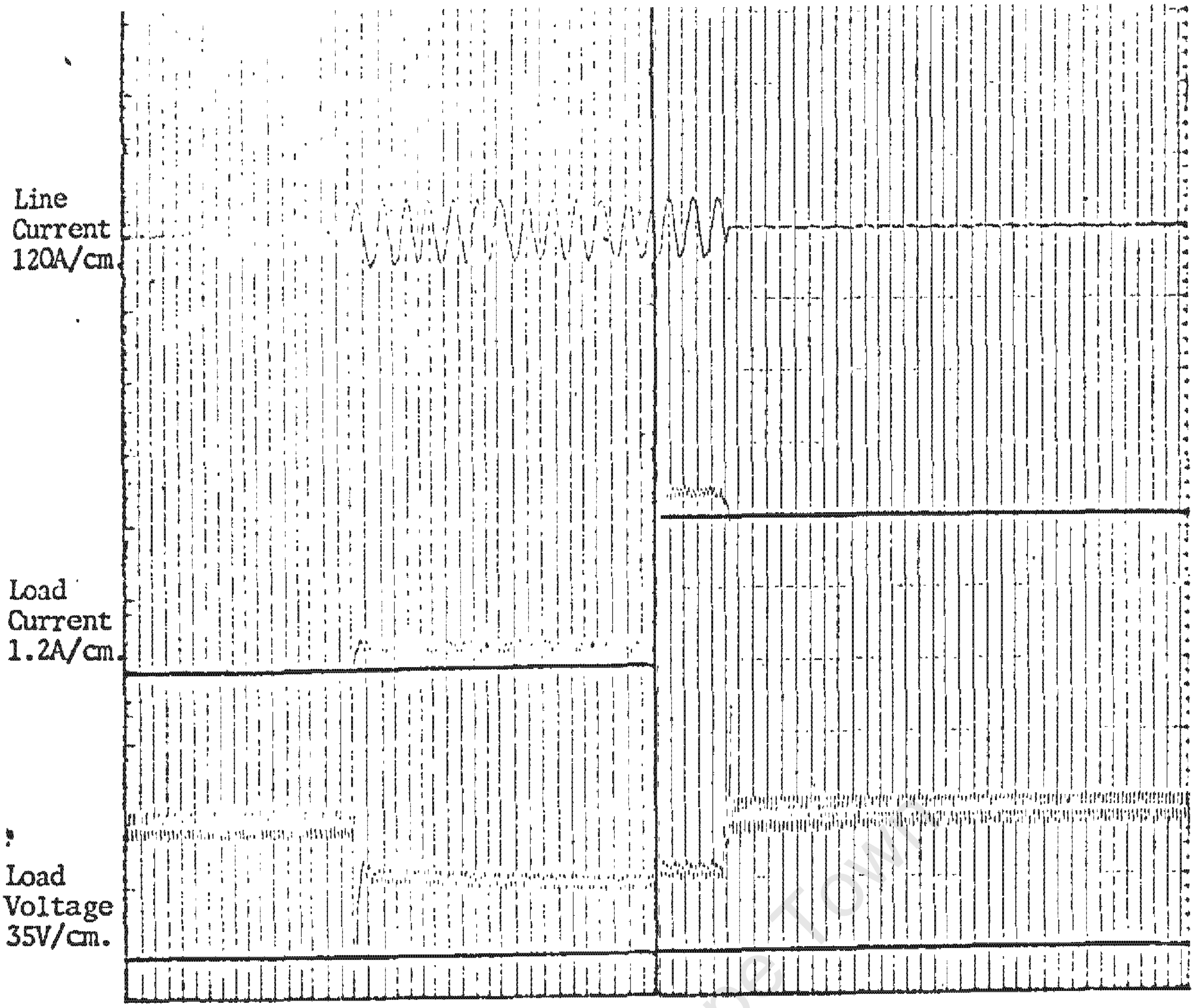
circuit.

If resistance is inserted in the output circuit and short and open circuit tests performed as before, the transient current rise is almost completely damped out as shown in Rec. 10.7(a) and (b) for 45 amps and 65 volts open circuit. This is however a very inefficient method of preventing current overshoot in welding generators.

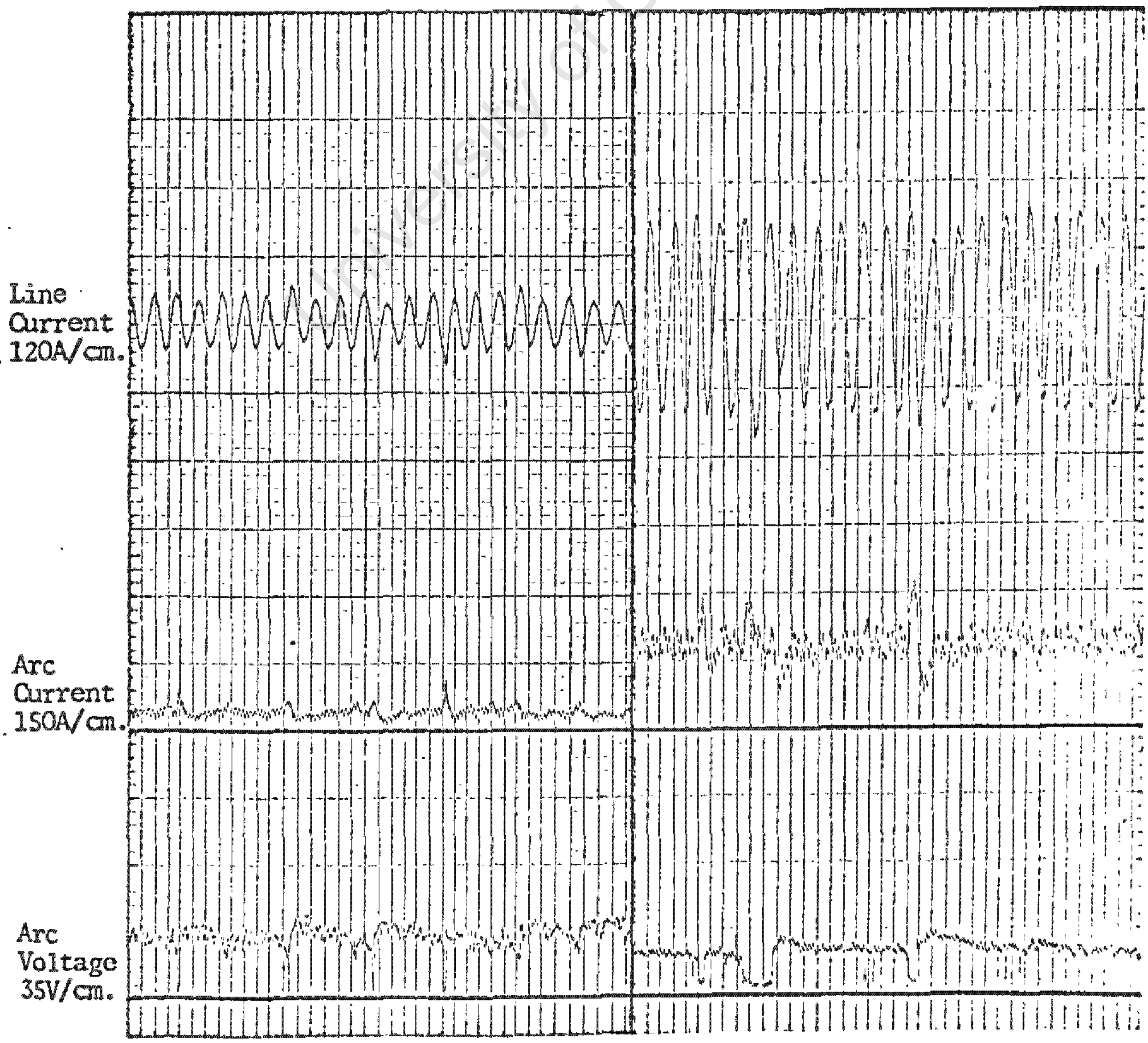
10.4.2 WELDING CHARACTERISTICS

A series of trial welds were made with the 3-phase reactor in the output circuit. The control circuit using current feedback is given in Fig. 10.3 and particular attention was paid to the weldability and arc stability obtained at the low current settings.

Rec. 10.8(a) and (b) shows current and voltage waveforms at 45 amps and 200 amps welding current, with the reactor airgap set at 1/8". Although there is a relatively large current variation when welding at 45 amps the overshoot and undershoot is not severe and the arc is quite stable. The small current surge when striking the arc did not cause overheating of the work and satisfactory welds were made on steel plate of 1/16" thickness. The current waveform when welding at 200 amps is generally of constant amplitude, except for over and undershoots when the arc is short circuited. However the arc is quite stable with no tendencies to 'snuff' out. Weldability is also satisfactory with easy control of metal deposition and good arc striking properties.



Rec. 10.7 a & b. Time-10mS./div.



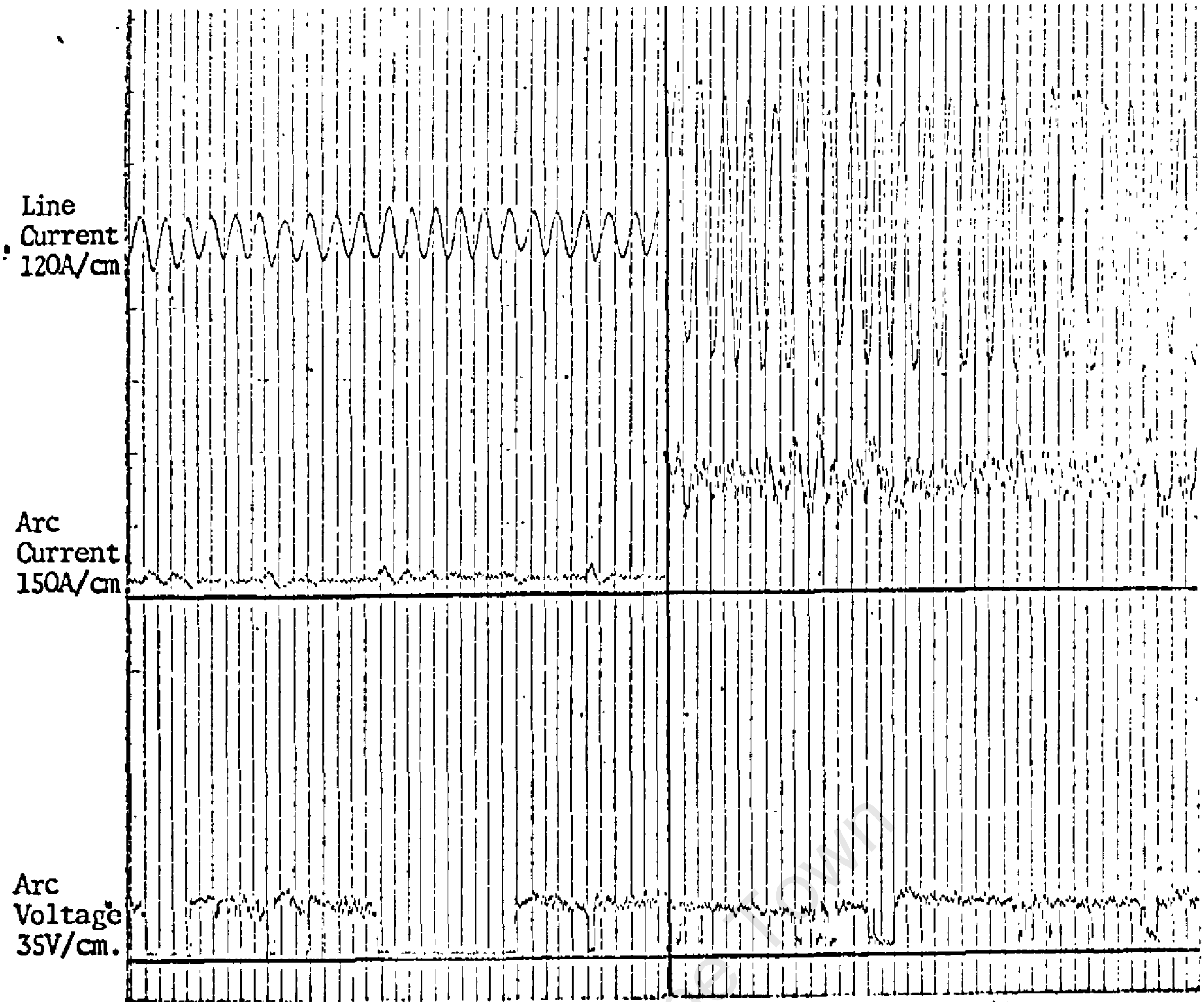
Rec. 10.8 a & b. Time-10mS./div.

Rec. 10.9(a) and (b) shows waveforms at 45 amps and 240 amps with a reactor airgap of 1/16". The current variations at 45 amps have been considerably reduced with over and undershoots at short circuit having smaller amplitudes even for arc shorts in excess of 50 mS. This characteristic produced a good quality weld with uniform metal deposition. As the current overshoots at short circuit are small it is necessary to maintain a constant arc length so that arc shorts are kept to a minimum. Without adequate current surges at short circuit the molten metal drop will not be removed fast enough and the short may continue too long, as shown in the recording.

The 240 amp waveform does show adequate current overshoot and good arc stability. At high currents the reactor will saturate and the inductance decrease to a low value causing increased variations in output current for transient load changes. Too much current overshoot on the other hand will increase metal spatter when welding and this is not easy to control by adjusting the arc length.

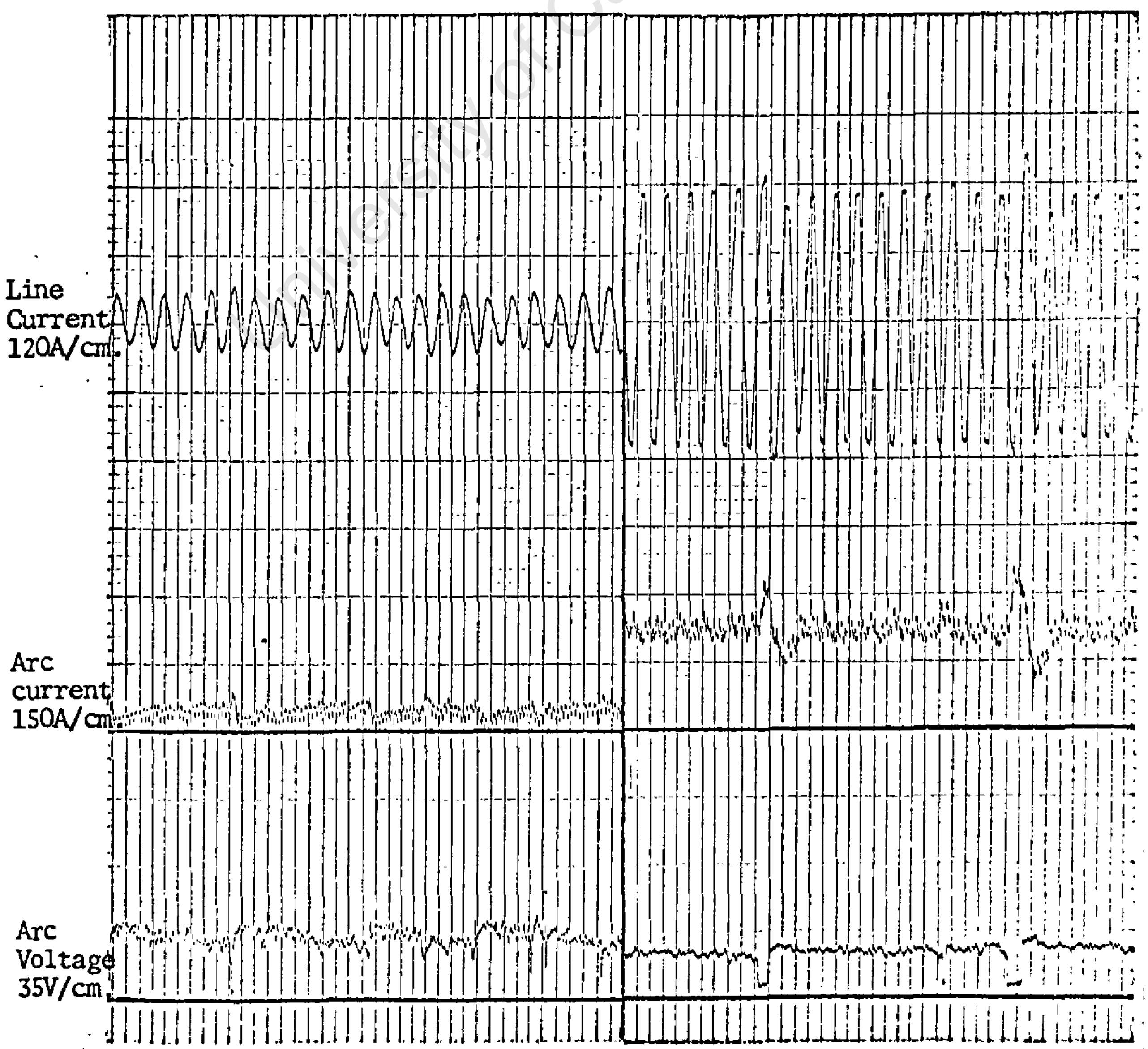
Rec. 10.10(a) and (b) shows welding characteristics at 45 and 200 amps when both the A.C. reactor and the D.C. choke are connected in the output circuit. The current waveforms are similar to those of Rec. 10.8(a) and (b) with the same degree of current variation and overshoot. There is increased ripple on the 45 amp waveform due to the additional inductance in the D.C. output circuit producing energy changes corresponding to the high rate of change of current in the output ripple from the

bridge/...



Time-10mS./div.

Rec. 10.9 a & b.



Time-10mS./div.

Rec. 10.10 a & b.

bridge rectifier.

There is thus no improvement in the welding characteristics using both types of output inductance simultaneously, as the A.C. reactor will control the large current transients and dampen the system before the D.C. choke has a chance to act. The D.C. choke thus serves no useful purpose in controlling damped current changes and becomes quite redundant in the output circuit.

11. WELDER CHARACTERISTICS WITH CONTROL CIRCUIT MODIFICATIONS

To enable the static characteristics of the welding generator to be varied so that the complete range of welding currents is obtainable on one control, the current feedback circuit has to be modified slightly. These modifications are also designed to vary the slope of the drooping voltage curves in the region of normal arc voltages. It will then be possible to approximate closely the constant current characteristics required by single operator D.C. welders for good weldability.

11.1 CHARACTERISTICS WITH CURRENT TRANSFORMER FEEDBACK

The basic control circuit is the same as given in Fig. 10.3, with current feedback from a C.T. in the output line of the alternator. The 3-phase reactor is also connected in the output lines as described in Section 10.4.

Although the welding characteristics obtained with this circuit arrangement were satisfactory there was interaction between the voltage and current controls on open circuit as described in Section 9.3. This could be eliminated if the current control was varied only by adjusting RCT, the burden resistance of the C.T. The disadvantage of this type of control is that the secondary current through the burden resistor increases rapidly up to the point of saturation of the core of the C.T. Beyond this point the output characteristic becomes non-linear which gives rise to an undesirable feature in the welding characteristics of the machine. It is also necessary to have series resistance in the field circuit to obtain the low range of welding currents. The circuit diagram used is given in Fig. 11.1.

To overcome these disadvantages and still maintain independent control of current and voltage it is necessary to have

a/...

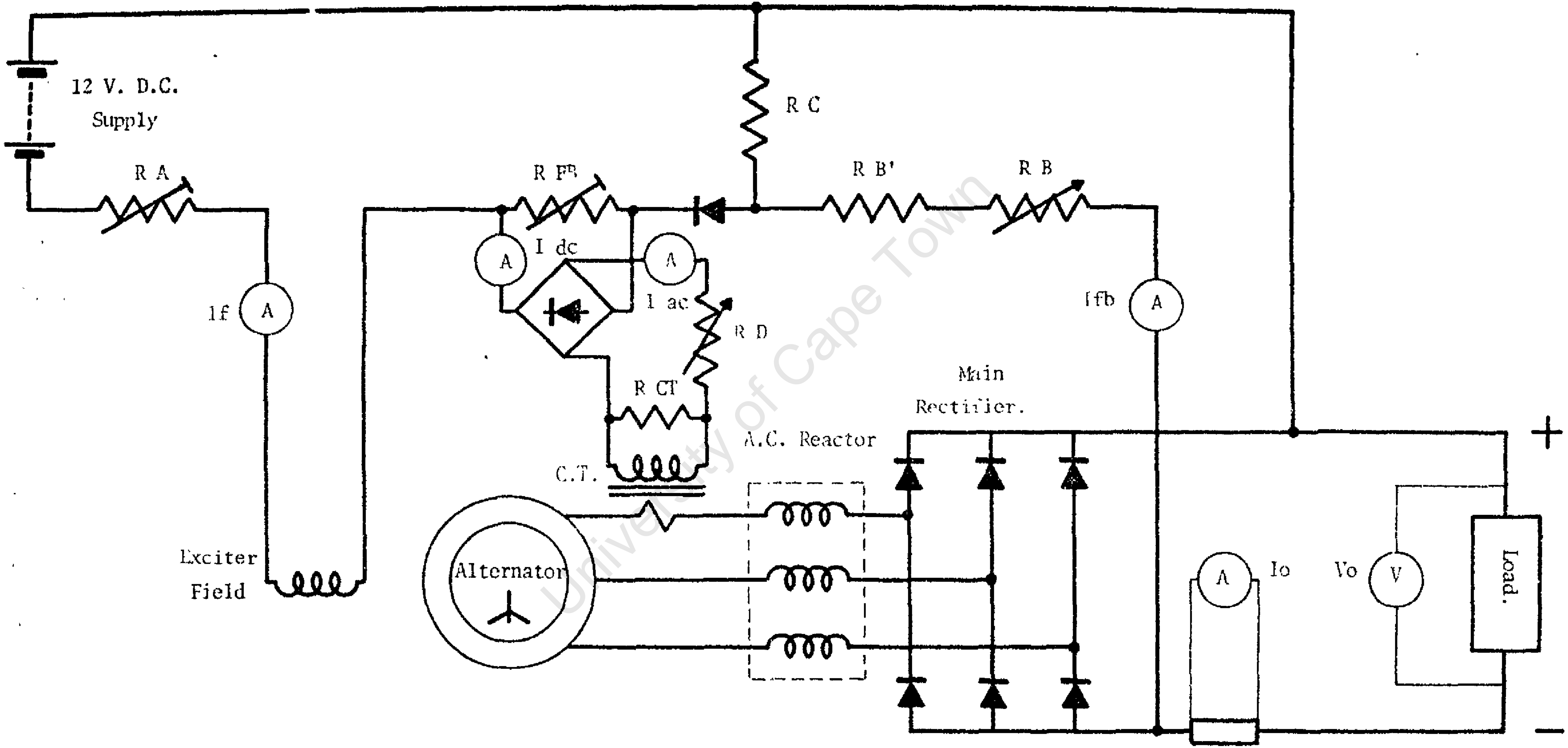


Fig. 11.1 Circuit Diagram with Current Transformer Feedback.

a fixed burden resistance RCT, and a series current feedback adjustment RD. At high values of RD there is more voltage drop across this resistor, than across the bridge rectifier supplying the field circuit and hence the field excitation is reduced.

The load characteristics for this type of control are similar to those of Fig. 9.2 with a steep slope of the curve in the region of normal arc voltages, but high voltage peaks at low currents when the value of RD is reduced to zero, for the high welding current ranges.

It is possible to reduce these voltage peaks if a shunt resistor RFB is connected across the D.C. output side of the current feedback bridge rectifier and the C.T. burden resistor is low enough to prevent saturation by reducing the output voltage from the C.T. The resistor RFB will reduce the proportion of current feedback to negative voltage feedback and thus the excitation will itself be reduced to prevent the voltage rising too high for increased values of load resistance. The value of RCT must not exceed 6 ohms, as a high burden resistance will increase the output voltage from the current transformer and produce a non-linear characteristic due to saturation. This will increase the proportion of current feedback to a level which cannot be counterbalanced by the shunt resistor RFB.

Although the high voltage peaks do not occur under normal welding conditions it is necessary to limit the output voltage to 100 volts at all times as a safety precaution for the operator.[4] The only possibility of obtaining this

high/...

high voltage is if the arc length is increased sufficiently to cause the arc resistance to exceed 0.25 ohms for welding currents less than 400 amps. This could occur when the arc is not broken properly at the end of a weld run and then only for a very short interval.

In order to obtain welding currents down to 40 amps it is necessary to have a low value of series resistance RA in the field circuit to limit the excitation without current feedback. The 12 volt supply to the field is thus too large to give the very low current range. As the series resistor RA is fixed at all times there will be no interaction between the welding current and voltage controls on open circuit and thus a precise setting of voltage can be maintained for the complete current range.

The load characteristics for the welder using the control circuit described here are given in Fig. 11.2. An open circuit voltage of 60 volts is taken in each case for different current settings.

The slope of these curves is not sufficient to prevent a large current variation at normal welding voltages so they do not represent true constant current characteristics.
In suppressing the high voltage peaks the welder characteristics have been changed to give an inferior current response although this does not affect the weldability to any great extent.

In order to retain these desirable constant current characteristics a different type of current feedback control circuit is investigated. As previously discussed in Section 8 the deposition of weld metal is directly related to arc current and thus a constant current will result in a uniform metal deposition.

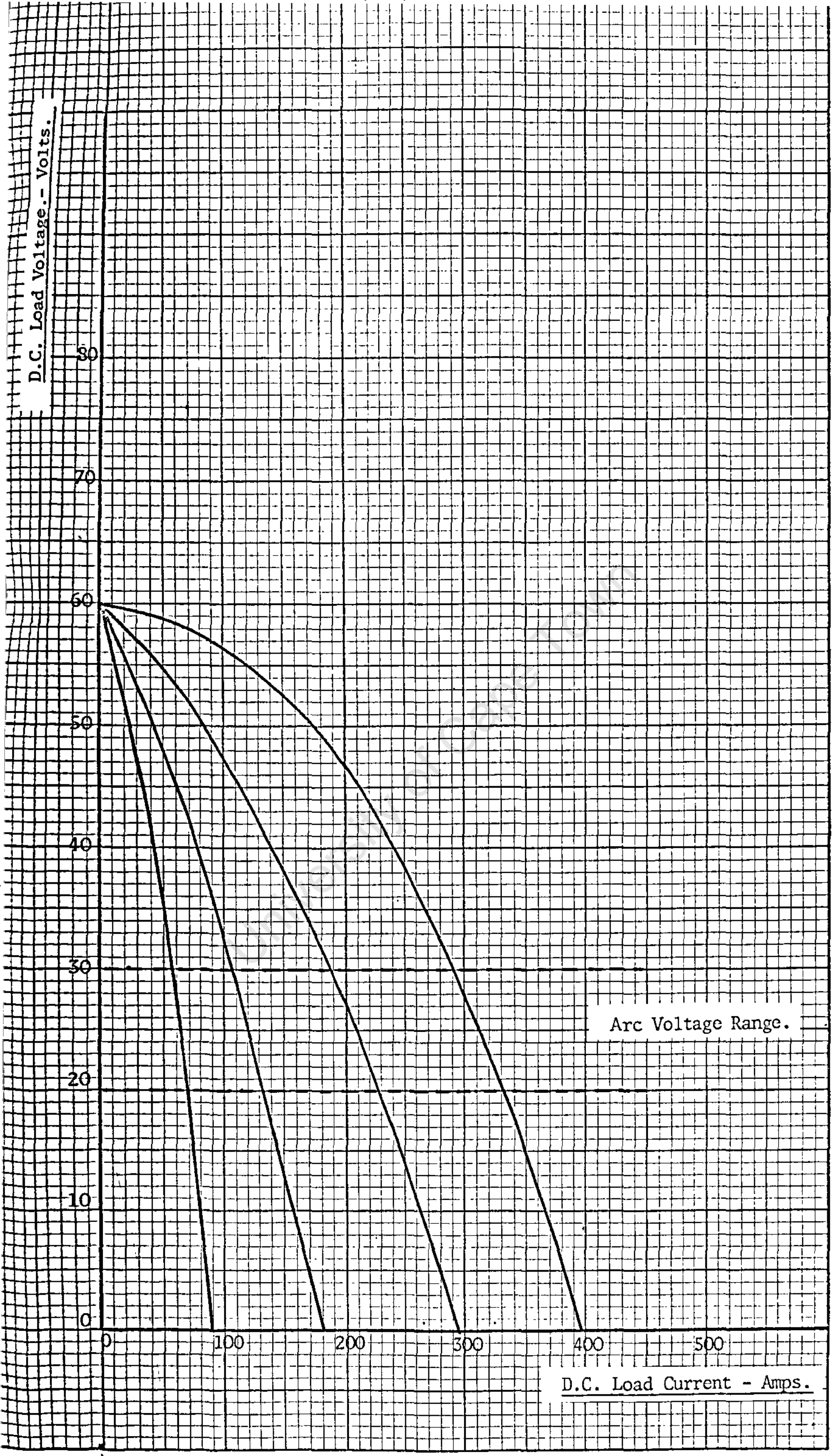


Fig. 11.2 Load Characteristics with Current Transformer Feedback.

11.2 CHARACTERISTICS WITH REACTOR VOLTAGE FEEDBACK

Instead of using a portion of the output current from the alternator as a means of increasing the excitation of the field, it is possible to use the voltage drop developed across a winding of the 3-phase A.C. reactor as positive feedback related to the magnitude of the output current.

As the current through the windings of the reactor increases, the voltage across a winding will increase depending on the state of saturation of the iron. This voltage must be isolated from the output circuit before being rectified and fed into the field exciter circuit as shown in Fig. 11.3.

An isolating transformer with adjustable tappings on the secondary side is used to obtain isolation and provide the excitation voltage required for the 'current' feedback circuit. Reducing the impedance of the secondary circuit as described in the previous section will effectively present a low impedance shunt to the reactor winding and result in high circulating currents. The series resistor RD can be used to adjust the amount of feedback to the field circuit and shunt resistor RFB is omitted to reduce the effective impedance of the secondary circuit.

A comparison between the equivalent current feedback voltages for the current transformer burden and the secondary of the isolating transformer is given in Fig. 11.4. These characteristics show that for the C.T. feedback the voltage is linear over a large current range and the voltages obtained at the higher output voltage peaks agree closely with those obtained for a short circuit load. On

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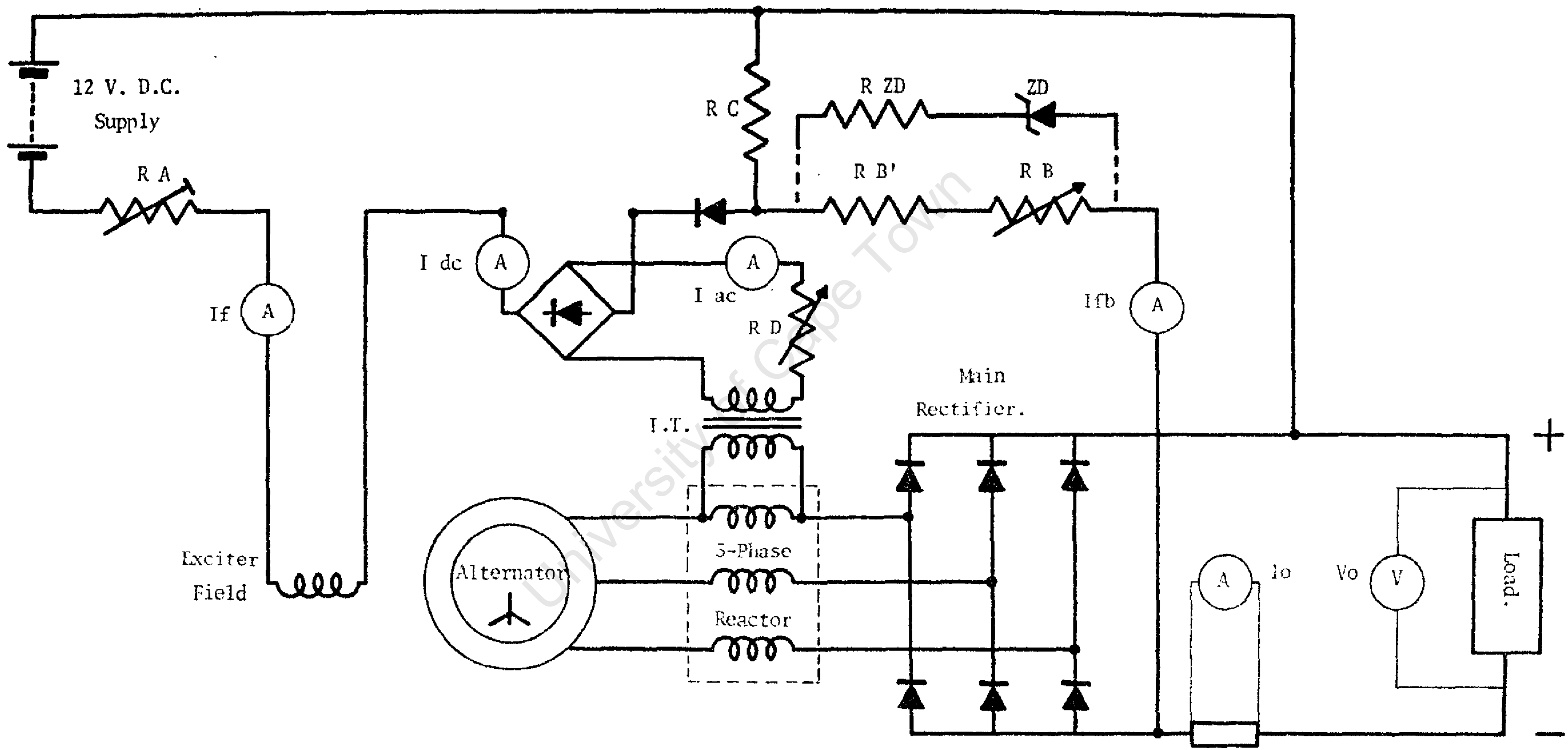

Fig. 11.3 Circuit Diagram with Reactor Voltage Feedback.

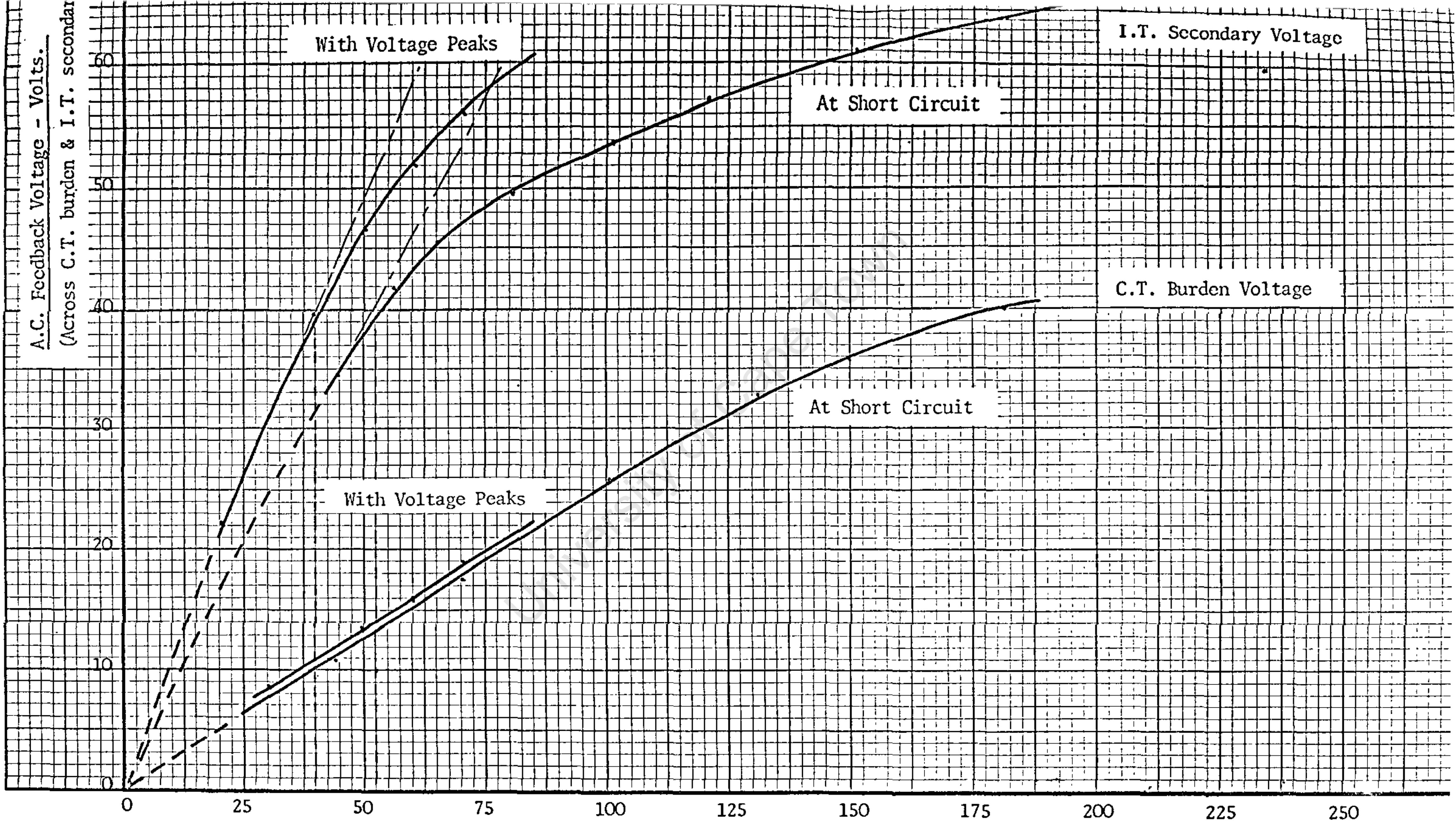

Fig. 11.4 Feedback Voltage Characteristics with C.T. & I.T. Feedback.

the other hand the voltage for the I.T. feedback is non-linear over the same current range and there is a marked difference between voltages obtained at the high output voltage peaks and those obtained for a short circuit load on the output.

The non-linearity of the I.T. feedback suggests that saturation of an iron core takes place at approximately 40 amps. This assumption is confirmed in Section 12.3 which gives the load characteristics of the 3-phase reactor. From Fig. 12.7 it is found that for a 1/16" airgap the reactor begins to saturate at 40 amps and the shape of the curves are the same, taking into account the voltage ratio of the isolating transformer.

The load characteristics obtained with this control circuit are given in Fig. 11.5 and indicate the extent of the voltage peaks produced for increased load resistance at high current settings. Although these voltage peaks are excessive, reaching 120 volts, the slope of the curves in the region of normal arc voltages of 20 - 30 volts is steep and approximates closely to that of constant current characteristics. The steep slope of the curves is due to the small change in the current feedback excitation when the A.C. reactor is operating in the saturated region. The voltage change across the reactor winding decreases relatively for increased current and this combined effect will limit the variation in arc current over a wide range of arc resistance.

It is thus desirable to retain the slope of these characteristics but to limit the maximum voltage to 100 volts. Two methods for limiting this voltage peak are to correct for the non-linear voltage characteristic obtained from

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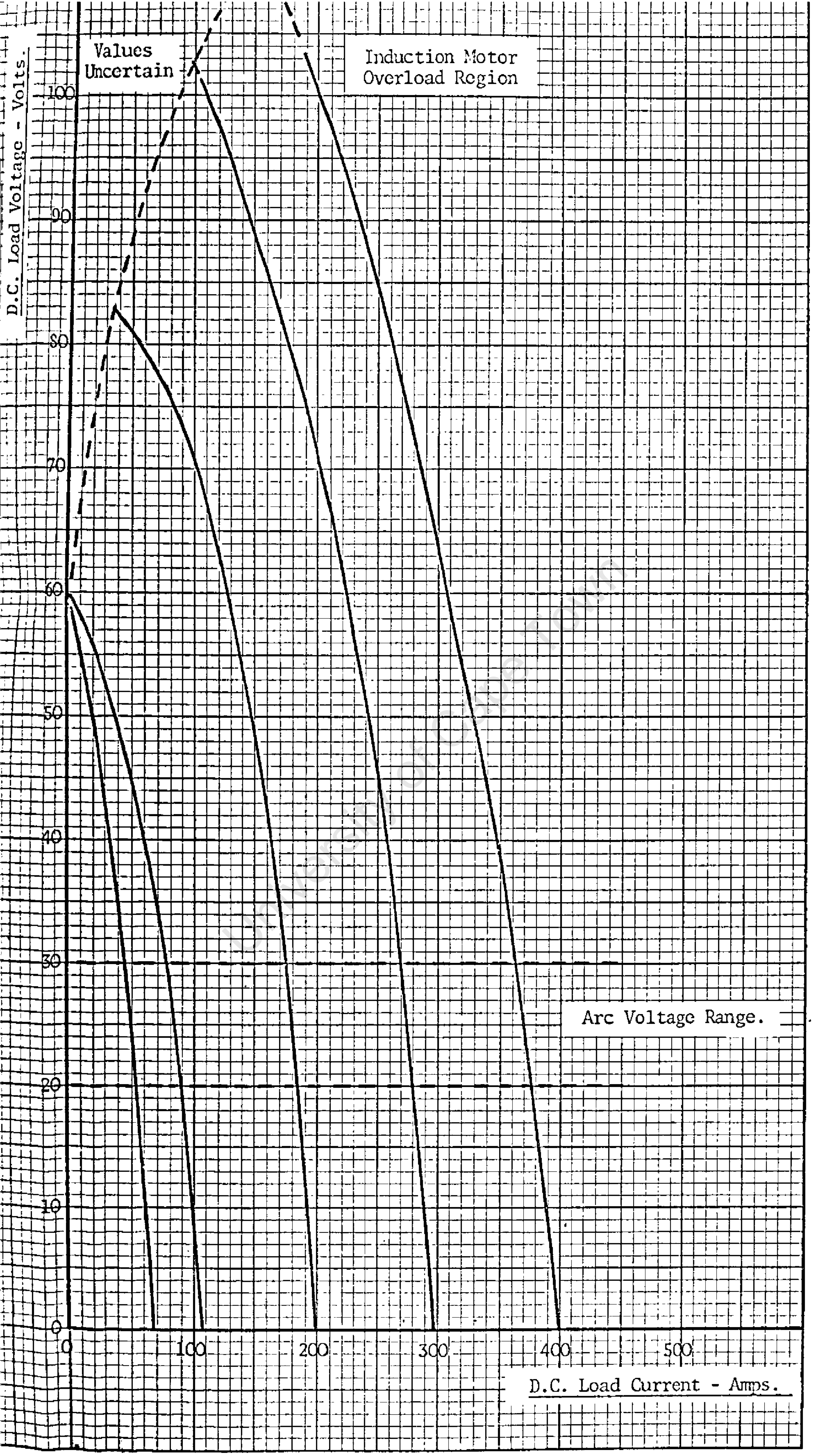


Fig. 11.5 Load Characteristics with Reactor Voltage Feedback.

the reactor at low currents or to increase the negative voltage feedback to the field circuit when the voltage approaches the 100 volt limit.

11.3 VOLTAGE LIMITING CONTROL

Both methods mentioned above for limiting the maximum voltage peaks require non-linear elements to correct for the inherent non-linear characteristics of the control circuit. To obtain a linear voltage output from the reactor over the whole current range it is necessary to either replace the reactor with one which does not saturate even at the highest current setting of 400 amps or to add a non-linear element in the feedback circuit whose resistance increases with increased current. The possibility of obtaining a reactor of the correct inductance which does not saturate at 400 amps is remote and the size would be prohibitive. A non-linear device whose resistance increases with current or the power dissipated, is a carbon filament lamp but such a device is unsuitable for this type of control circuit and would not add to the reliability of the welder if in continuous service.

If the negative feedback to the field excitation circuit is increased when the voltage approaches the 100 volt limit then the reduced field current will cause the voltage to fall below the limit. By decreasing the feedback resistors RB or RB^1, the feedback current Ifb, is increased and this will cause the field current If to decrease. As the output voltage is divided across resistors RC and RB + RB^1 in series, the voltage drop across RB + RB^1 is a fixed proportion of the output voltage for a particular setting of RB^1

because/...

because the resistor RC is always fixed. By connecting a Zener diode of a suitable rating across $RB + RB^1$ the voltage will be limited to a set level and if attempting to rise above this level, the diode will conduct and effectively reduce the feedback resistance and thus increase the feedback current Ifb. The output voltage will consequently be reduced below the maximum limit.

The Zener diode acts purely as a safety device only operating when the output voltage reaches the 100 volt limit which may occur with a sudden increase in arc resistance when the arc is broken.

This method of maximum voltage control also overcomes the effect of the non-linear voltage feedback variation with increased field currents, which has previously been discussed in Section 5 and shown in Fig. 5.4.

Fig. 11.3 shows the position of the Zener diode across voltage feedback resistors RB and RB^1. The diode voltage rating is 70 volts and 75 watts to take the increased feedback current at voltage peaks. (Type BZY 91 - C68)

The improved load characteristics are given in Fig. 11.6 and show the reduced voltage peaks.

As a further comparison between the characteristics obtained with Current Transformer or Reactor Voltage feedback, Heat Output curves are given in Figs. 11.7(a) and (b).

The heat output curves for C.T. feedback obtained from the load characteristics in Fig. 11.2 are given in Fig. 11.7(a). These curves agree with the typical heat output curves of Fig. 2.3. They show the amount of heat produced at the arc, determined by the product of voltage and current for a particular point on the load characteristic curve. This heat

output/...

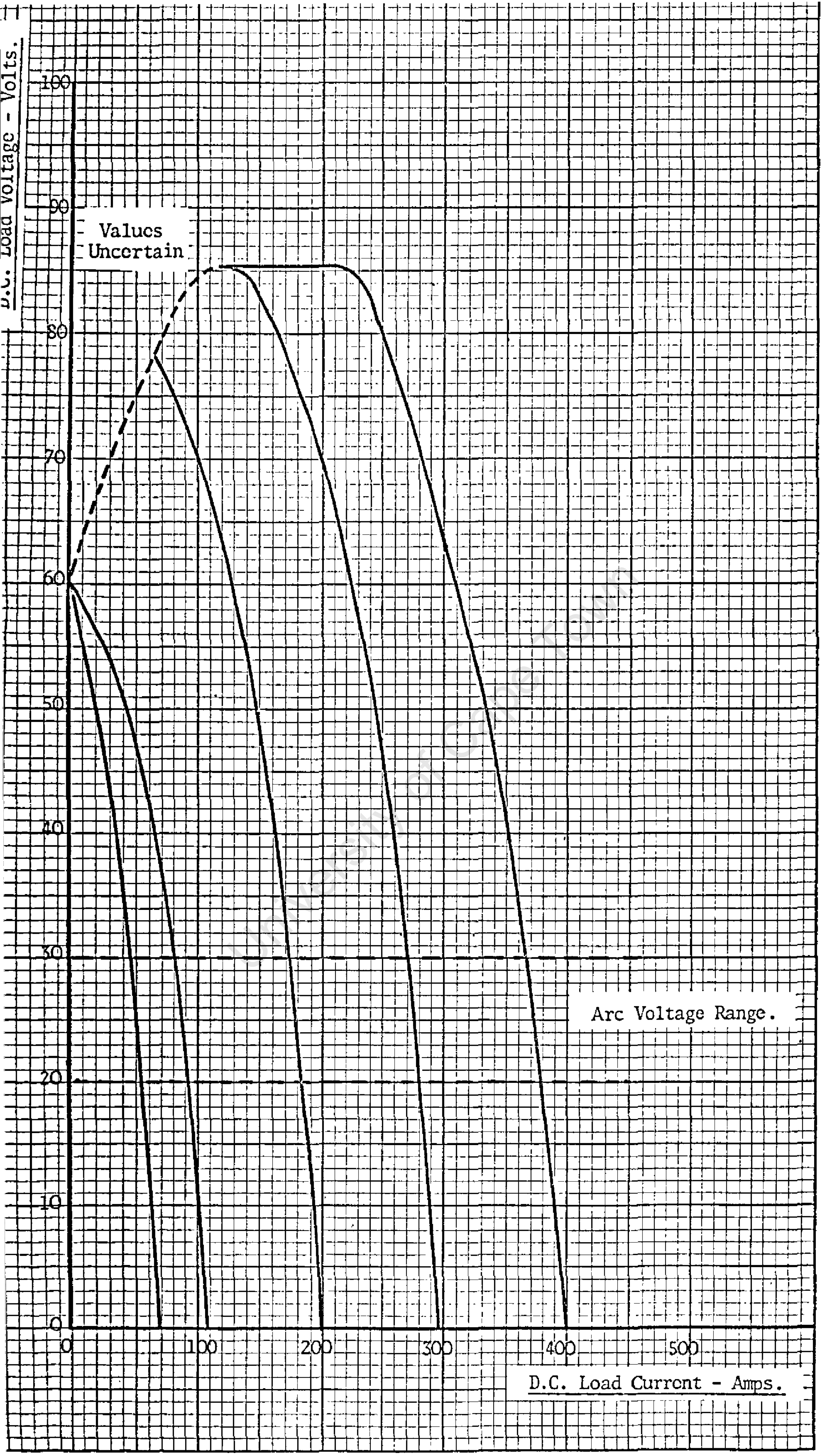


Fig. 11.6 Load Characteristics with Output Voltage Limit.

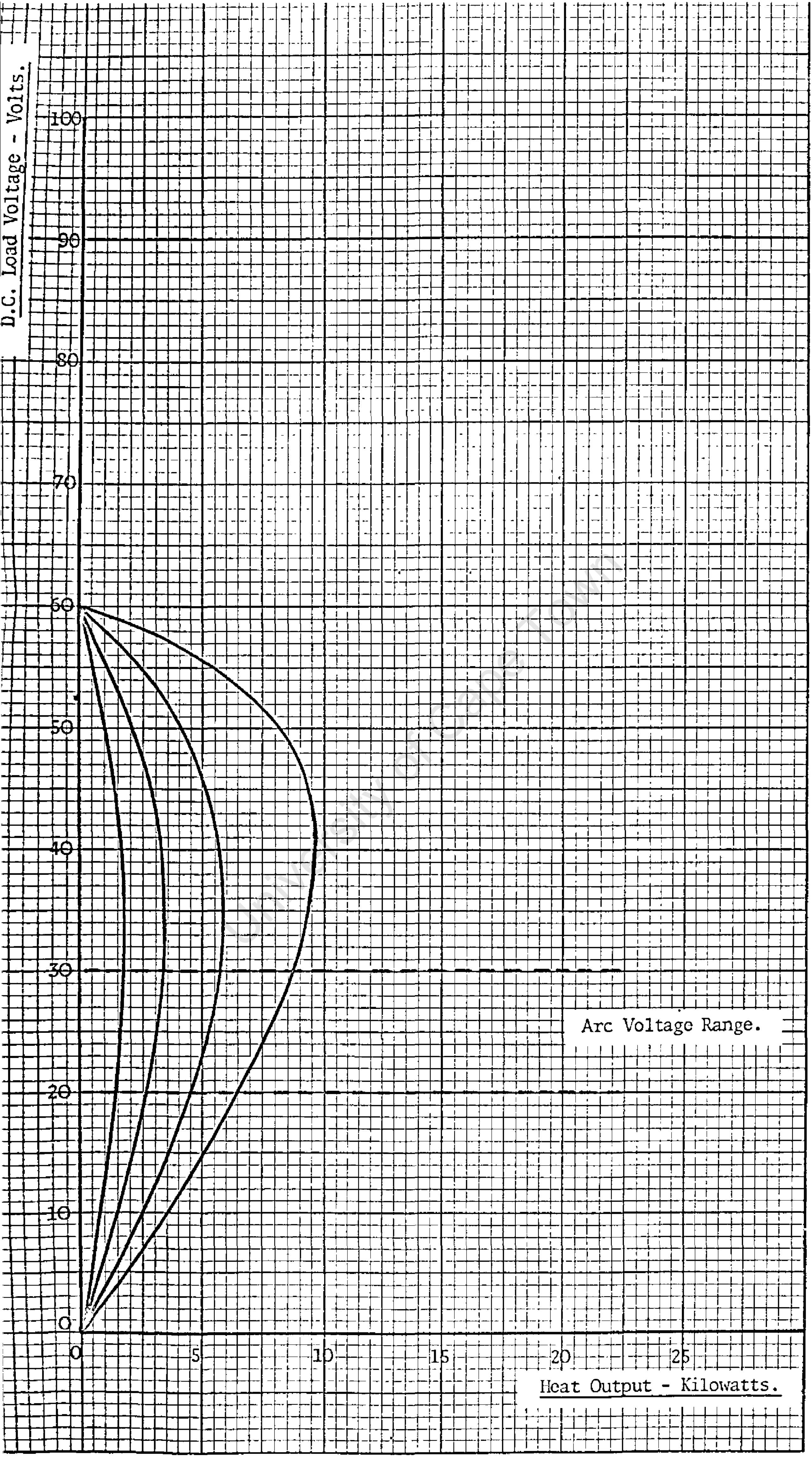


Fig. 11.7(a) Heat Output Curves with Current Transformer Feedback.

output decreases for shorter arc lengths over the range of normal arc voltages. However as the metal deposition rate is dependent on the arc current, decreasing the arc length will increase the amount of metal deposited, as discussed in Section 8.

Fig. 11.7(b) shows the heat output curves obtained from the reactor voltage feedback characteristics in Fig. 11.5. Although these curves are similar to those of Fig. 11.7(a) in the region of normal arc voltages, at increased voltages there is considerable difference. The power dissipated in the arc increases rapidly when the arc length is increased and reaches a maximum near open circuit voltage. This indicates that the arc is still stable for long arc lengths but control of metal deposition is not possible in this region. For normal welding operations however the arc voltage seldom exceeds 35 volts, with reduced heat output.

11.4 <u>CONTROL CIRCUIT FUNCTIONS</u>

A schematic block diagram of the system is given in Fig. 11.8 and this represents a Second Order System with a Major and Minor Feedback Loop.

The 12 volt D.C. supply reference is taken from the diesel driving engine battery and this voltage should not vary appreciably or the current and voltage control settings will be affected.

Complete independence of current and voltage control is achieved with this sytem and a set open circuit voltage will remain constant over the full current range settings.

The basic design and layout of the control panel is given in the following Section.

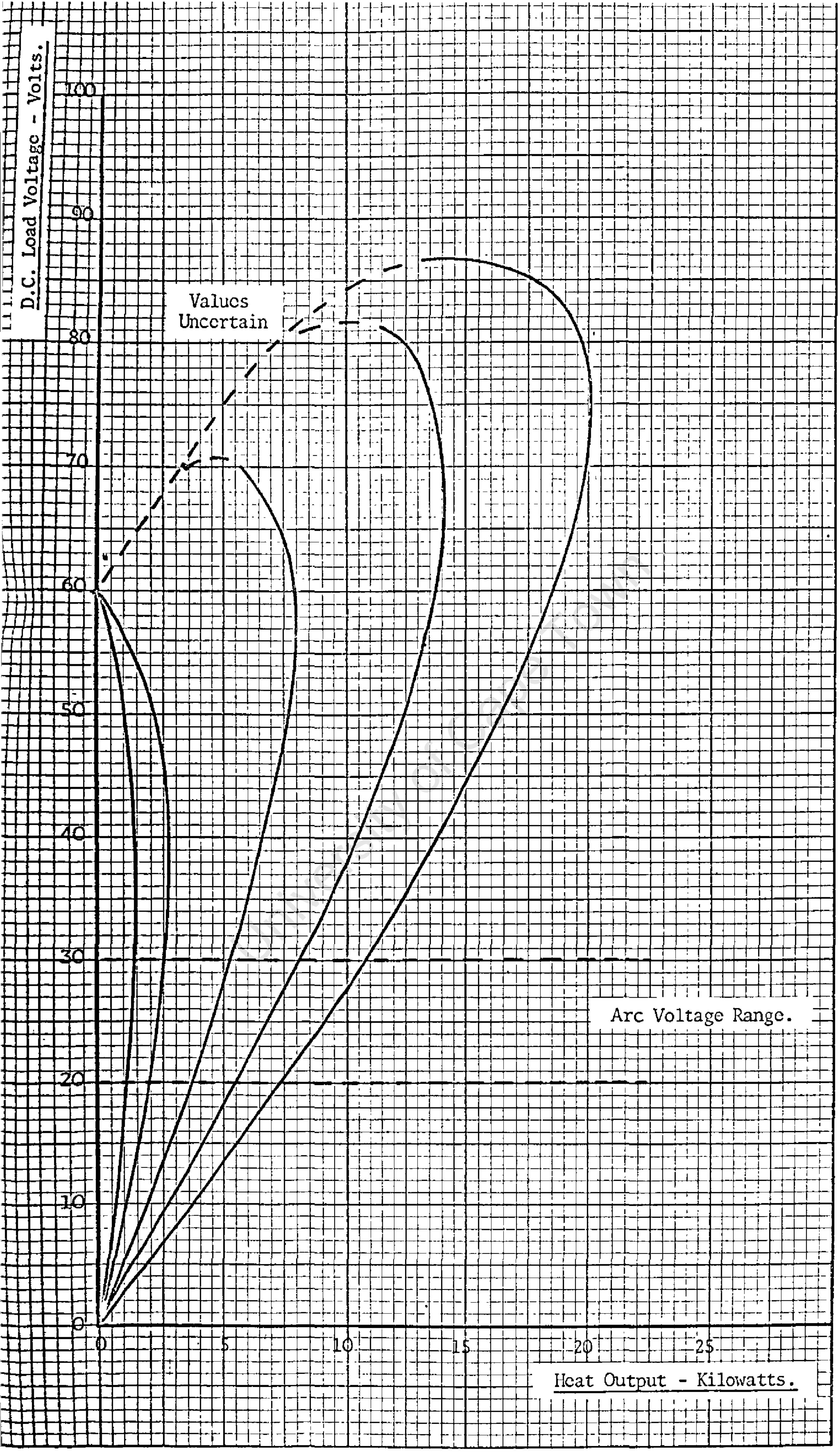


Fig. 11.7(b) Heat Output Curves with Output Voltage Limit.

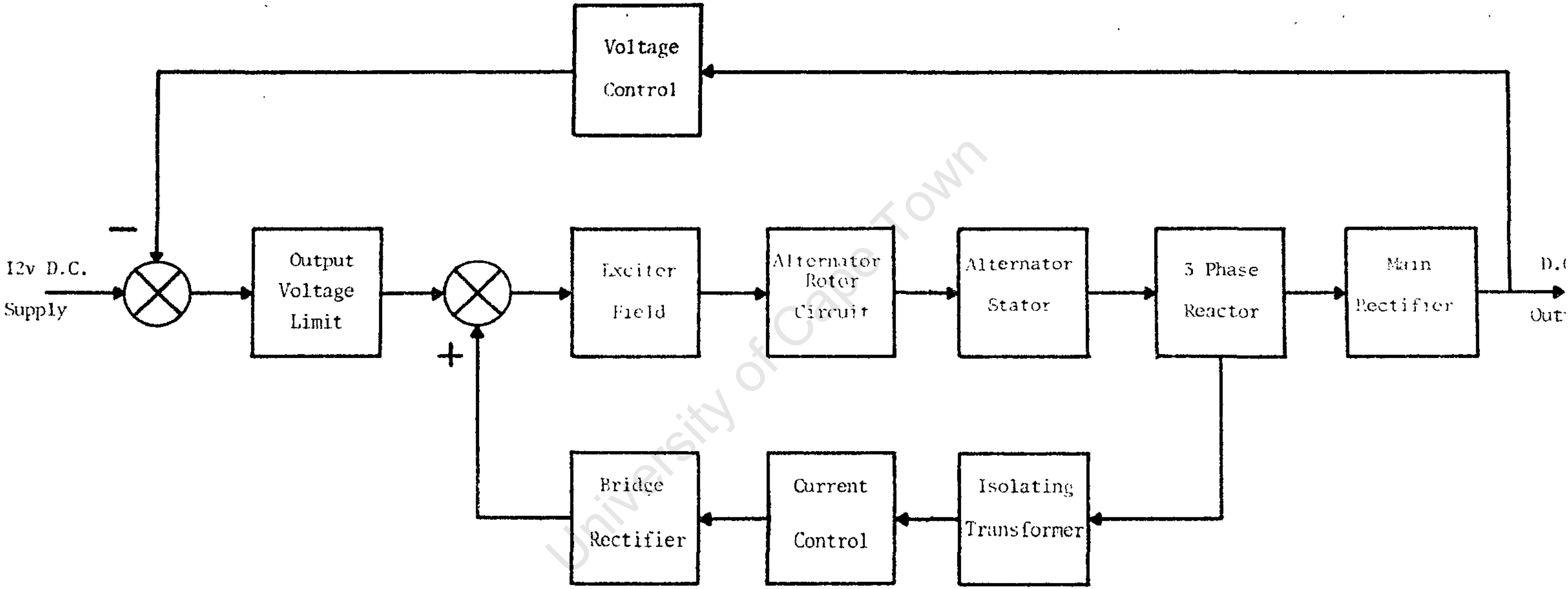


Fig. 11.8 Schematic Block Diagram of Control Circuit.

12. DESIGN OF THE GENERATOR SET

As outlined in Section 1.2 of the Introduction, there are to be two sets of controls for the power plant. One half for the A.C. power supply and the other for the D.C. welding output. A single switch must be incorporated in the circuit so that either supply can be selected at any time and there must be complete isolation between supplies so that with one on, the other is quite 'dead'. The component layout should be compact and built around the alternator to save space and the control cubicle with power and welding controls should be mounted at the end of the generating set.

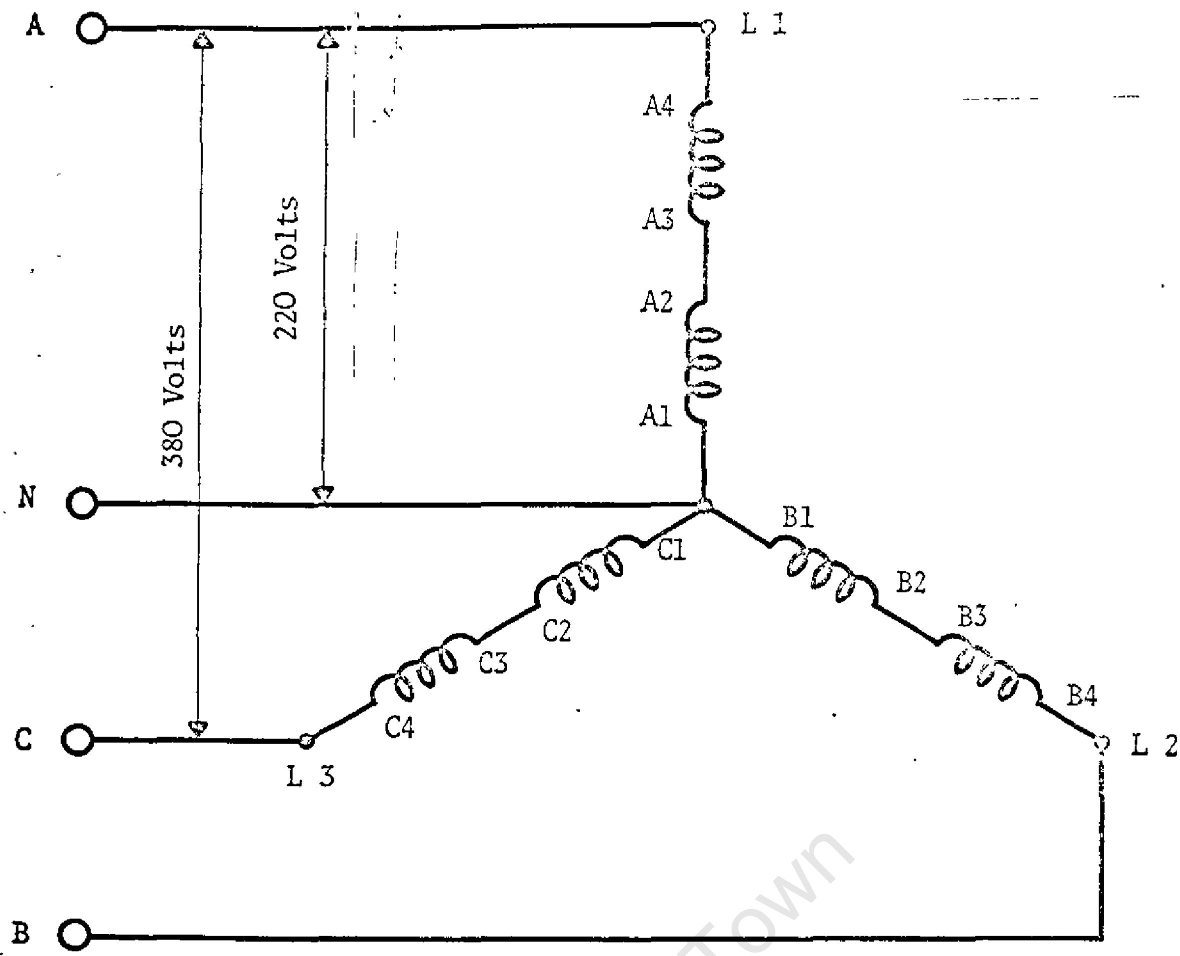
The design of the major components which make up the complete set, is given in the following sub-sections.

12.1 CHANGE OVER SWITCH

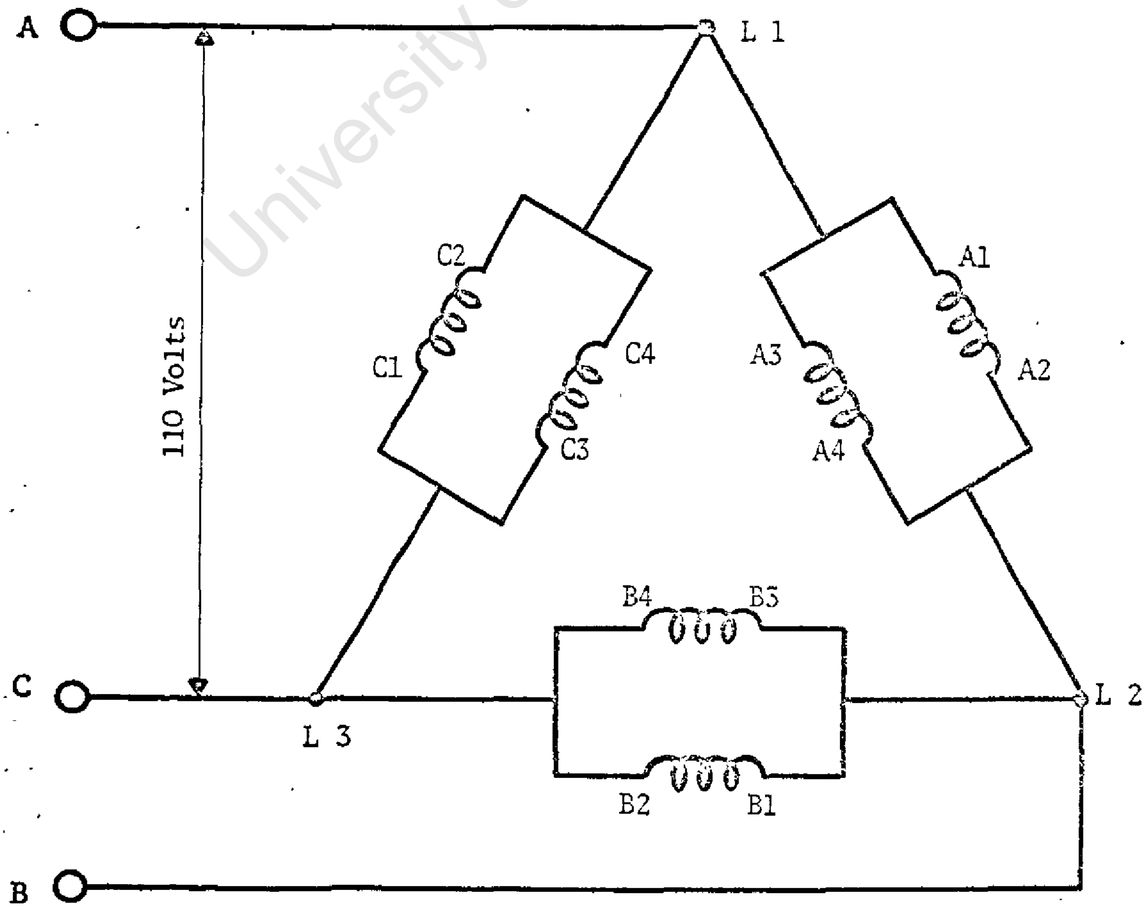
The main change over switch is necessary to reconnect the stator windings of the alternator when switching between the Power and Weld positions. As described in Section 2 the stator windings are connected in series-star for Power supply and in parallel-delta for Weld output. The layout of the stator windings for each connection is given in Fig. 12.1 together with winding numbers for the B range machine.

All stator winding ends are brought out to the main terminal board, fixed to the top of the alternator. Connections between the winding terminals are made with short links enabling the different winding layouts to be easily selected. The linking arrangements for the series-star and parallel-delta windings are given in Figs. 12.2 and 12.3 respectively. The difference in the linking arrangements forms the basis for selecting a switch with the right contact layout, keeping the switch size to a minimum.

After/...



Series-Star Winding for Power Supply.



Parallel-Delta Winding for Welding Output.

Fig. 12.1 Stator Connections with Winding Numbers.

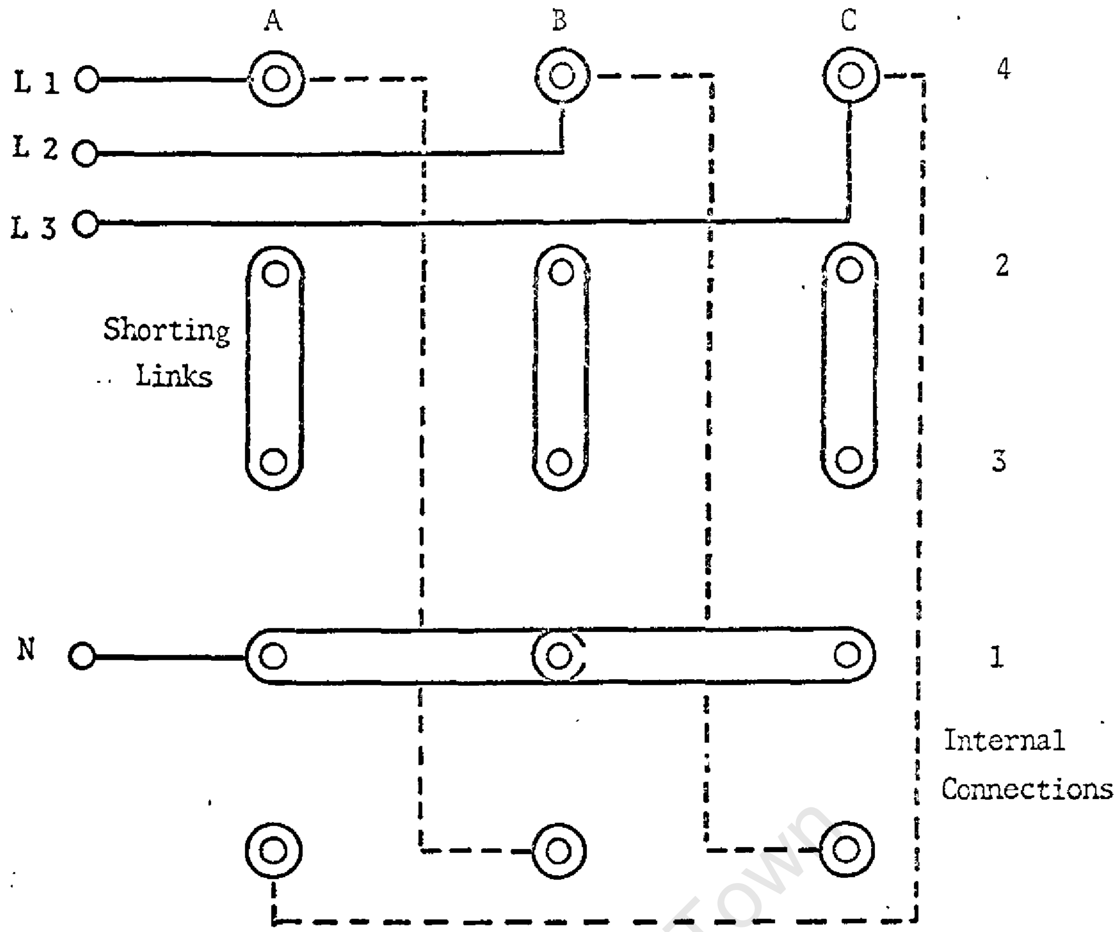


Fig. 12.2 Link Connections for Series-Star Winding

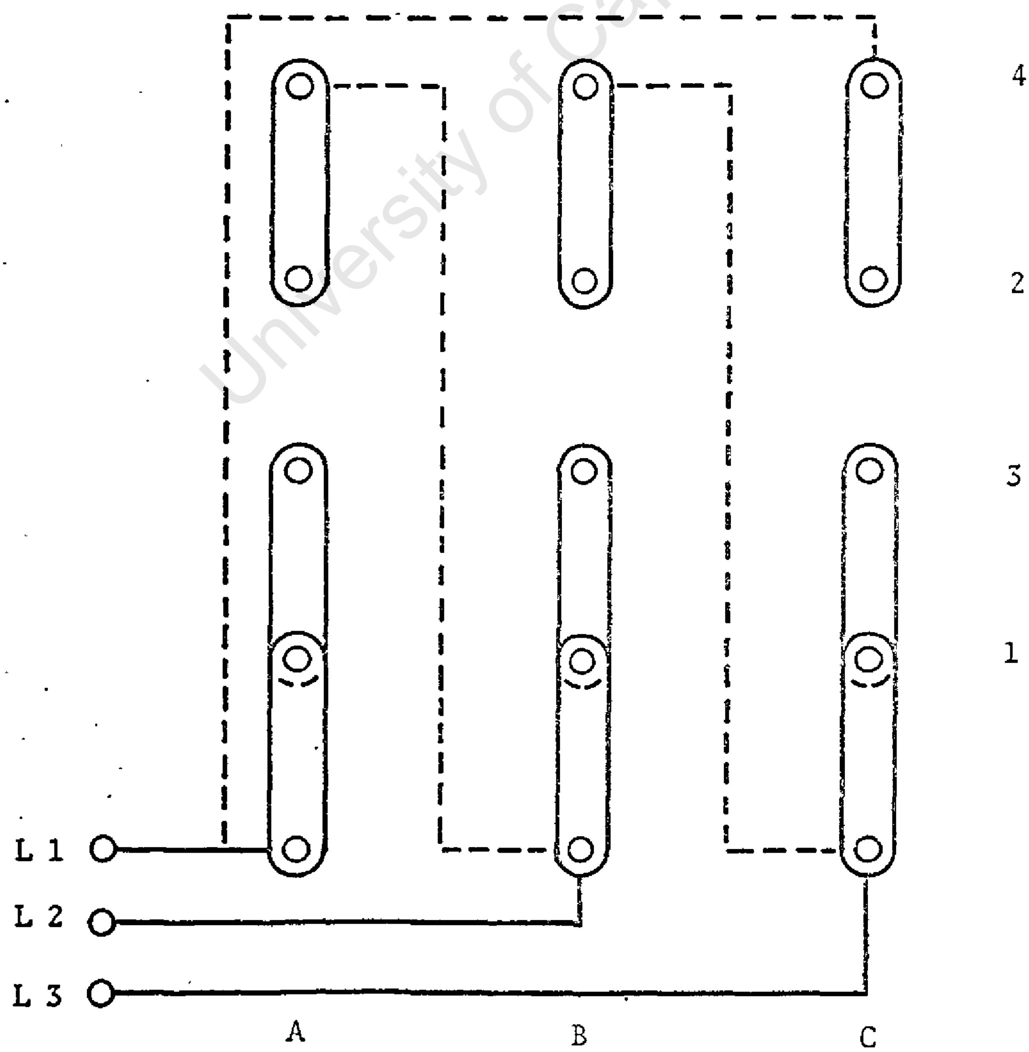


Fig. 12.3 Link Connections for Parallel-Delta Winding

After considering many variations of contact layout, the arrangement given in Fig. 12.4 was adopted as being the most suitable. This is a 9 pole 2 way change over switch giving the necessary reconnection of stator windings. It can be seen from the contact layout that with the switch in the Power position all three output terminals for the welding supply are shorted together, making the D.C. output cables quite 'dead'. In the Weld position all four output terminals for the power supply are completely isolated and thus quite safe to handle. The actual switch used has 200 amp current carrying contacts and as the current through the contacts with output connections L1, L2 and L3 on the Weld side, may exceed 200 amps, an additional 3 poles are connected in parallel with these output contacts.

An auxiliary switch is necessary to select the different exciter field control circuits required for Power and Weld operation. When operating in the Power position the field winding and stator reference voltage leads are connected to the Automatic Voltage Regulator unit. In the Weld position just the field winding leads are connected to the welding control circuit. This switching arrangement thus requires a 4 pole 2 way low current switch to be operated in conjunction with the main selector switch.

The switching sequence on the actual switch used with the auxiliary and main switches coupled in tandem on a 30° movement is:

0° - Centre	=	OFF
30° - Left, Pos. 1	=	POWER ONLY
60° - Left, Pos. 2	=	POWER + EXCITATION
30° - Right, Pos. 1	=	WELD ONLY
60° - Right, Pos. 2	=	WELD + EXCITATION

The/...

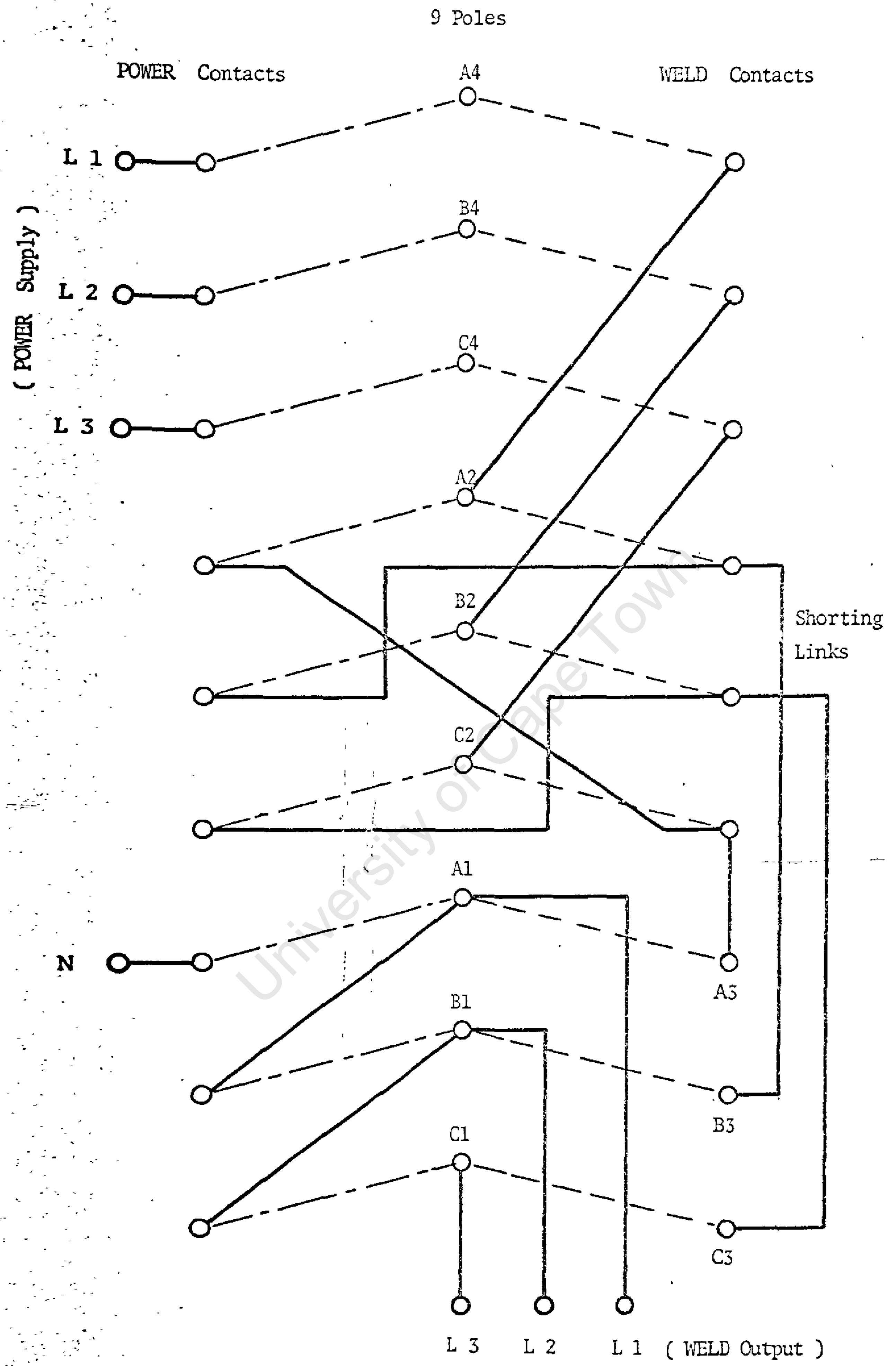


Fig. 12.4 Main Switch Contact Layout.

The stator windings are connected for Position 1 and the excitation is switched on for Position 2. Therefore the main 200 amp switch is only used as an isolator thus giving longer contact life with frequent operation. The alternator is not subjected to severe transient loading when switched onto permanently connected loads, if the excitation is switched on after the load circuit is made.

The layout of the Selector Switch and other components on the alternator is given in Fig. 12.5, which also shows the position of the Control Cubicle in relation to the rest of the unit. The mounting base and driving engine have been omitted from the figure as these are to be designed at a later stage.

12.2 MAIN RECTIFIER

A 3-phase, full wave, bridge rectifier is used to provide the D.C. output from the alternator and the diodes and heatsink should be designed to handle the maximum current of 400 amps used for welding.

The theoretical conversion factors for A.C. to D.C. current and voltage are as follows:

$$I_{\text{A.C. (line)}} = .816\ I_{\text{D.C.}}$$

$$I_{\text{DIODE (RMS)}} = .577\ I_{\text{D.C.}}$$

$$I_{\text{DIODE (AVE.)}} = .333\ I_{\text{D.C.}}$$

and $$V_{\text{D.C.}} = 2.34\ V_{\text{A.C. (Phase)}}$$

These conversion factors for an equivalent double 3-phase rectifier are briefly discussed in Appendix 3.[5]

Thus for a 400 amp D.C. output:

$$I_{\text{A.C. (Line)}} = .816 \times 400$$

$$= 326 \text{ amps}$$

For/...

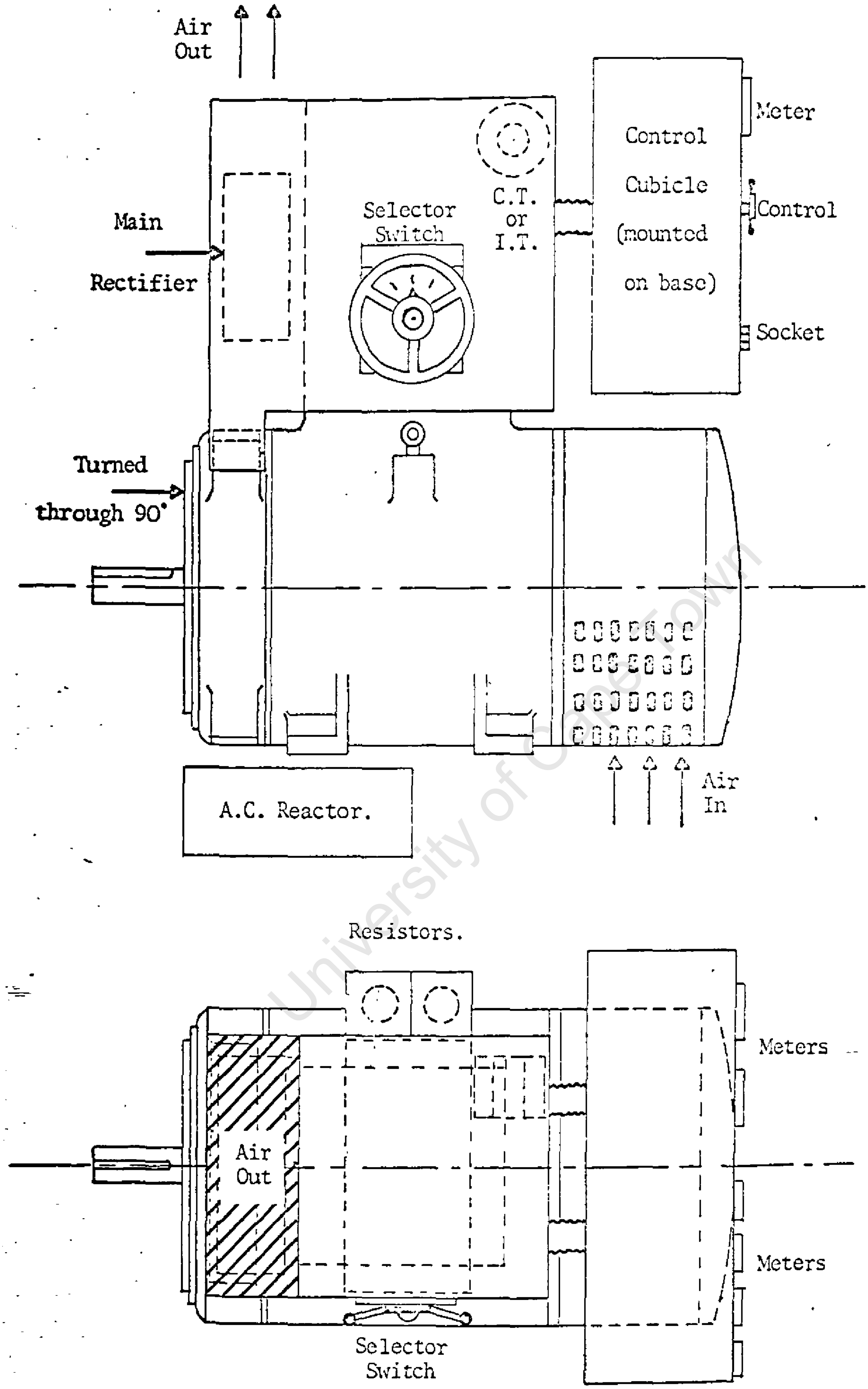


Fig. 12.5 Layout of Components on Alternator.

For each diode in the bridge:

$$I \text{ DIODE (Rms.)} = .577 \times 400$$
$$= 230 \text{ amps}$$

and $$I \text{ DIODE (Ave.)} = .333 \times 400$$
$$= 133 \text{ amps.}$$

For a maximum D.C. working voltage of 100 volts:

$$V \text{ A.C. (Phase)} = \frac{100}{2.34}$$
$$= 43 \text{ volts}$$

or $$V \text{ A.C. (Line)} = 43 \times \sqrt{3}$$
$$= 74 \text{ volts.}$$

Then Peak Inverse Voltage $= 74 \times 2$

$= 105$ volts.

12.2.1 DIODE RATINGS

The actual diodes used for the welding generator are Sarkes Tarzian Silicon, Type ST 740. These were available from previous work in this field[3] and their ratings are:

$$I \text{ (Ave.)} = 160 \text{ amps}$$
$$V \text{ (Rms.)} = 280 \text{ volts}$$
and $$V \text{ (P.I.V.)} = 400 \text{ volts}$$

The maximum D.C. current output using these diodes in the bridge rectifier will be

$$I \text{ D.C.} = 3 \times 160$$
$$= 480 \text{ amps.}$$

This is in excess of the maximum current rating of the generator and with the welding current control

set/...

set for a maximum possible current output of 400 amps D.C. there is no apparent need for special semi-conductor fuses in the A.C. lines from the alternator.

Unfortunately there are no short-time surge ratings available for these diodes but values for other diodes of similar size are:

Non repetitive peak forward current (10 mS)
= 3000 amps

Repetitive peak forward current = 750 amps.

The voltage ratings of the diodes are much greater than those of the generator and as these are silicon diodes with controlled avalanche voltage characteristics they are able to withstand high reverse transient voltage peaks.

12.2.2 HEATSINK DESIGN

In order to take advantage of the forced ventilation through the machine for cooling the diodes, the heatsink is mounted above the air outlet from the alternator front-end cover. This cover has been turned through 90° so that the air exhausts vertically up and down and the diodes heatsink are mounted in a separate compartment as shown in Fig. 12.5.

Owing to the small space available above the air outlet, the heatsink has to be designed as small and compact as possible without causing the diodes to overheat. For maximum cooling the surface area of heatsink in the air stream should be as large as possible without actually hindering the flow of cooling air through the machine.

To determine the required heatsink cooling area per diode, calculations on thermal resistance and junction temperatures are as follows:

Assume maximum I DIODE (Ave.) = 140 amps.

Now Forward Power Loss, $P = .95 \times Vf \times I$ (Ave.)

where Vf = Forward voltage drop across diode

and I (Ave.) = Average diode current.[6]

Internal Thermal Resistance of diode,

$$Si = \frac{Tj - Tmb}{P} \quad {}^{o}C/Watt$$

where Tj = Junction Temperature, ^{o}C.

Tmb = Mounting-base Temperature, ^{o}C.

Heatsink Thermal Resistance to air,

$$Sh = \frac{Tmb - Ta}{P} \quad {}^{o}C/Watt$$

$$= \frac{Tj - Ta}{P} - Si \quad {}^{o}C/Watt$$

where Ta = Cooling Air Temperature, C.

Typical values for Silicon Diodes are:

$Si = 0.2$ C/Watt

$Tj = 160^{o}C$ ($190^{o}C$ maximum)

$Vf = 1.3$ Volts.

Then Power Loss:

$$P = .95 \times 1.3 \times 140$$

$$= 173 \text{ Watts}$$

For $Ta = 40^{o}C$ then:

$$Sh = \frac{160 - 40}{173} - 0.2$$

$$= 0.695 - 0.2$$

=/...

$$= 0.495 \quad {}^{o}C/Watt.$$

Base temperature, $Tmb = Sh \times P + Ta$

$$= 0.495 \times 173 + 40$$

$$= 125\,^{o}C.$$

For a cooling air velocity of 2000 ft/min., approximately 35 sq. inches of 16 gauge Aluminium are required per diode to maintain this base temperature.

A more accurate method which takes into account the Contact Thermal Resistance is as follows:[7]

From information on diodes of similar rating such as the BYX 14 series; and for the same I DIODE (Ave.) = 140 amps per diode

Total Power Loss = 220 Watts

The Thermal Resistance of Mounting-base to Air:

$$Rth(mb - a) = 0.38 \ {}^{o}C/Watt$$

and Contact Thermal Resistance to Heatsink:

$$Rth(mb - h) = 0.07 \ {}^{o}C/Watt.$$

Hence Heatsink Thermal Resistance to Air:

$$Rth(h - a) = Rth(mb - a) - Rth(mb - h)$$

$$= 0.38 - 0.07$$

$$= 0.31 \ {}^{o}C/Watt.$$

For Heatsink calculations:

$$Tj. - Tamb. = P \times (Rth(j - mb) + Rth(mb - h) + Rth(h - a))$$

where Tamb. = Ambient temperature of air, ^{o}C

and $Rth(j - mb)$ = Thermal Resistance of Junction to Mounting base

$= 0.28 \ {}^{o}C/Watt$ for diode.

Thus/...

Thus $T_j - 40 = 220\ (0.28 + 0.07 + 0.31)$

$= 220 \times 0.66$

$= 145$

$\therefore \quad T_j = 145 + 40$

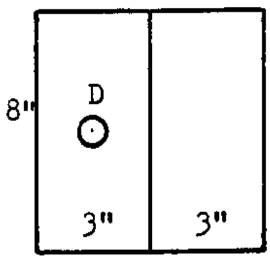
$= 185\ ^{\circ}C.$

This is within the maximum allowable value for $T_j = 190\ ^{\circ}C$, and is only effectively realised for a 30% duty cycle of the generator's maximum current output.

For the equivalent cooling air velocity of 10 metres/sec. approximately 180 sq. cms. of 3 mm. Aluminium are required per diode. This agrees closely with the values obtained from the previous calculations, allowing for the heavier gauge of aluminium specified.

If the heatsink area for one diode is arranged as in the following sketch then the complete heatsink may be constructed as given in the plan view of Fig. 12.6.

3mm
Aluminium



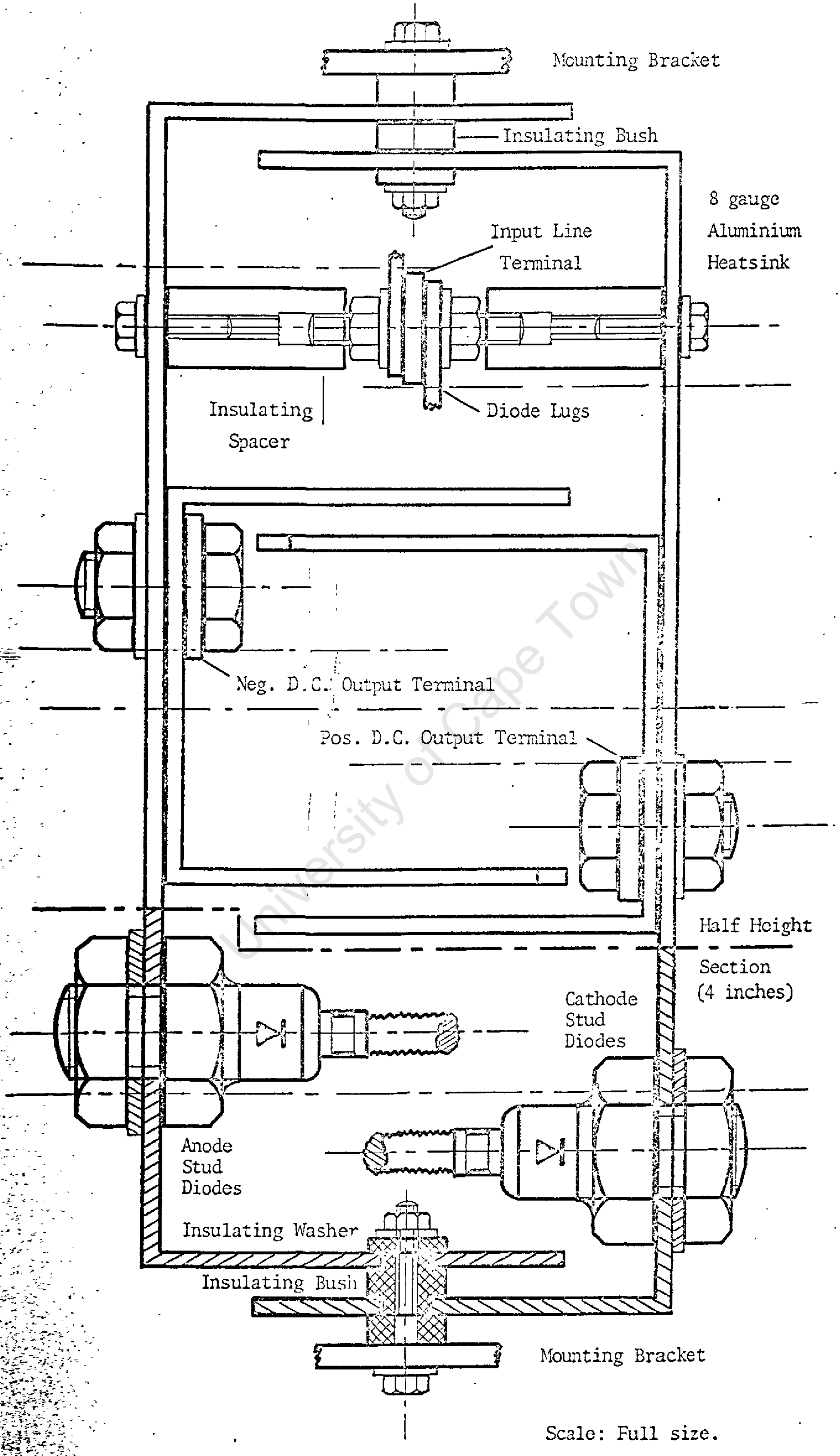
Area = 48 sq. ins.

= 310 sq. cms.

Three of the six diodes are 'reverse' polarity diodes enabling one side of the heatsink to be a positive terminal and the other side the negative terminal for the D.C. welding output.

Although the diodes and the A.C. input connecting spacers are close together the net air space area is greater than the air outlet port area of the alternator end cover. Thus the passage of air

through/...



Scale: Full size.

Fig. 12.6 Plan View of Rectifier Heatsink. (8 inch height.)

through the machine and passed the rectifier stack is not restricted in any way.

12.3 A.C. REACTOR

As it was decided to abandon the use of a D.C. Choke in the output circuit to modify the machine's transient characteristics, no details of the actual design of the chokes are given here. Values for the inductance of the chokes at 50 Hz are given in Section 9.4 when investigating the transient characteristics of the machine.

Fortunately a suitable 3-phase A.C. reactor with adjustable airgap was found in one of the Electrical Engineering Department stores. This reactor was found to be quite suitable for use in the three output lines of the alternator and produced very satisfactory results as described in Section 10.4.

The reactor has three separate limbs with a common airgap at one end that can be adjusted for 1/16, 1/8 of 3/16 inch thickness.

Core cross section = 2" x 2"

= 4.0 sq. inches

Number of turns on one limb:

= 22 turns.

As there is no information available on the type of iron used for the reactor a load test is carried out to determine at what current the iron saturates.

The reactor is connected in circuit and the alternator placed on a resistive load. The voltage drop across one winding is measured for increasing line currents and the

results/...

results are plotted in Fig. 12.7.

With an airgap of 1/16 inch the iron begins to saturate at approximately 40 amps which corresponds to a Flux density of 0.7 $Wb./m^2$. For the 1/8 inch airgap however the iron reaches saturation at approximately 65 amps which corresponds to a somewhat lower Flux density of 0.54 $Wb./m^2$. This is due to the increased airgap reluctance which reduces the Flux over the same area.

Calculations of the inductive reactance for the different airgaps show that for:

1/16 inch airgap:

At 50 amps, Inductance/winding = 1.27 mH.

At 200 amps, Inductance/winding = 0.45 mH.

1/8 inch airgap:

At 50 amps, Inductance/winding = 0.86 mH.

At 200 amps, Inductance/winding = 0.44 mH.

Thus to obtain the maximum inductance per winding over a wide current range it is best to use a 1/16 inch airgap.

Although the reactor will saturate for currents in excess of 40 amps, the inductance at this level is sufficient to prevent severe current undershoot when welding and so maintain arc stability. Current overshoot is also present as shown in the Recordings of Section 10.4, but this is within acceptable limits and does not cause excessive metal spatter.

The position of the A.C. reactor on the generator set is shown in Fig. 12.5 and is placed in the outlet air stream from the alternator to provide a small amount of forced cooling for the windings.

The winding size is of 5/16 inch square cross section and

at/...

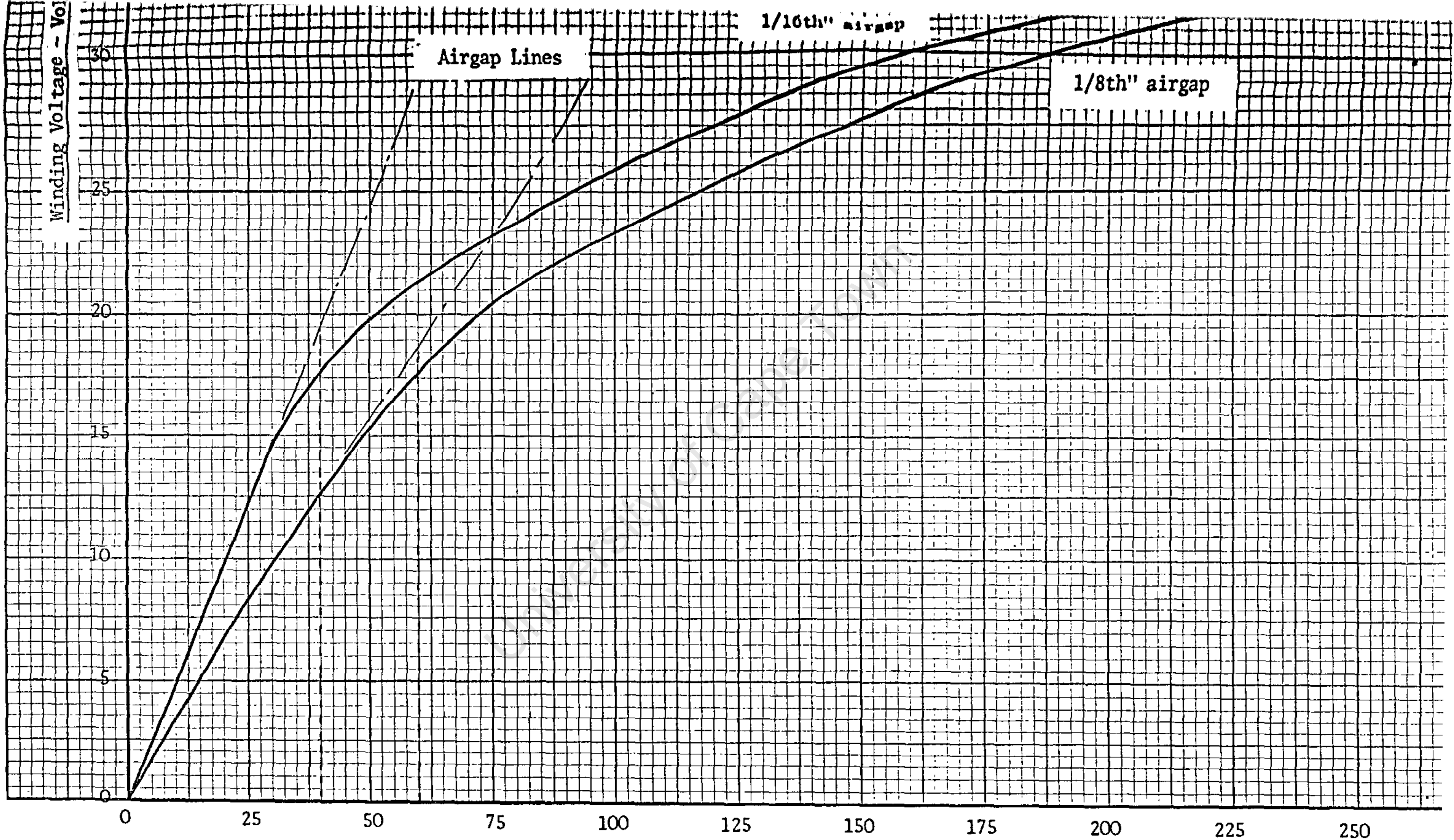


Fig. 12.7 Load Characteristics of 3-Phase Reactor.

at a current density of 2500 amps per sq. inch, the current rating is 240 amps continuous at 100% duty cycle. This rating is comparable to that of the alternator but the reactor has better cooling properties with a ¼ inch air space between layers. The temperature rise of the reactor will thus not be the limiting factor on the overall rating of the generating set.

12.4 WELDING CONTROL CIRCUIT

The final control circuit is similar to that described in Section 11.2 and is given in Fig. 12.8. Typical circuit component values are also quoted but these may have to be changed slightly when the complete generating set is assembled.

The basic layout of the control panel is given in Fig. 12.9 with the 3-phase supply instruments on the left and the welder controls on the right. Provision is made for a remote control current adjustment enabling 'on the spot' control of the welding current. An additional feature is the switch and push-button which provides a 12-14 volt, 400 amp D.C. supply for starting motor vehicles without their batteries.

Protection circuits incorporated into the basic control circuit consist of:

(a) Overvoltage protection.
Should the voltage feedback control fail and the output voltage exceed 100 volts a voltage sensitive relay will trip the field excitation supply. This relay can only be reset by hand after the fault has been cleared. Repeated tripping of the relay will

indicate/...

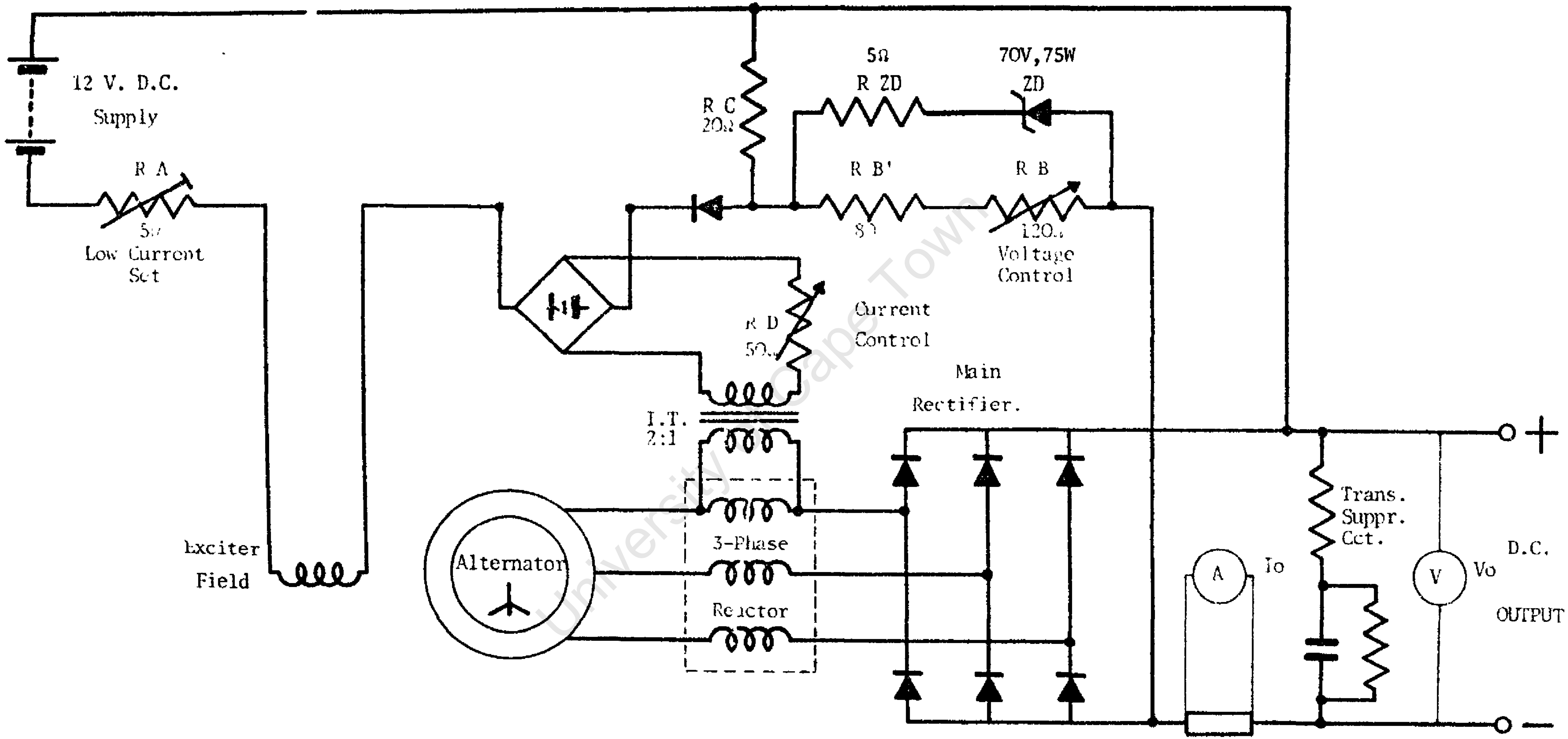


Fig. 12.8 Circuit Diagram of Complete System.

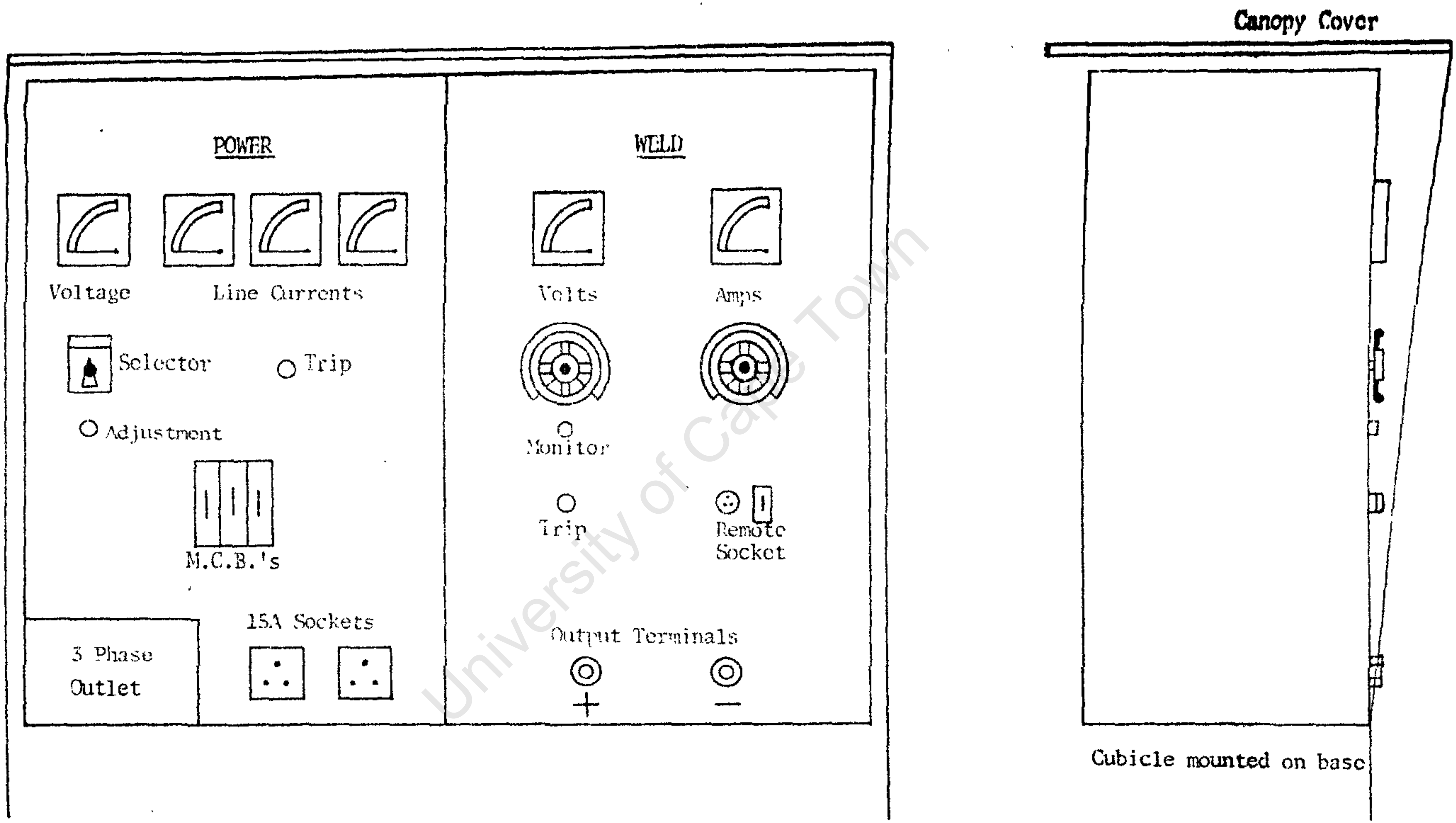


Fig. 12.9 Basic Layout of Control Panel.

indicate a major fault and require a thorough inspection.

(b) Overload protection.

A standard temperature sensitive switch or thermistor is embedded in the stator windings of the alternator. If the winding temperature exceeds a specified limit the switch will energise a warning light or the relay trip coil. When the temperature falls to a permissible level again the light will go out and the relay reset itself for normal operation.

(c) Transient Voltage Protection.

A simple resistor-capacitor circuit is connected across the D.C. output of the machine to prevent high transient voltage spikes from damaging the diodes in the main rectifier. As these diodes are of the controlled avalanche type they are able to withstand high voltage transients so the suppressor circuit serves as an added precaution in this case.

13. CONCLUSIONS

The objectives of the research carried out for this thesis, as listed in Section 1 of the Introduction have been accomplished.

In the process of developing this welding generator using a brushless industrial alternator, much knowledge on the nature of the D.C. welding arc load and the associated transient characteristics of the machine was acquired.

The most important single fact arising from all the research carried out is that the machine must have the correct type of transient characteristics to short and open circuit conditions before it can operate successfully as a welding generator. This fundamental requirement is incorporated in the design of all D.C. machine welders and attempts to solve the problem by field control met with little success as described in Sections 6 and 7. However, by the addition of inductance in the output of the alternator, the transient and sub-transient reactance of the machine could be increased sufficiently to produce the required characteristics for good weldability.

The design of a suitable control circuit to adjust the operating range of the welder is accomplished using voltage and current feedback from the output of the generator. Apart from the few essential diode elements the rest of the control circuit components are passive resistor or transformer devices giving the simplicity and reliability required of this type of equipment for industrial use. An important feature of the excitation control is that the same single exciter field winding is used for both the 3-phase A.C. supply and the D.C. welding output, without having to split the winding for series or parallel connection.

The most important part of the generating set has already been assembled; this being the main change over switch and rectifier stack which are mounted in a partitioned cubicle above the alternator. Changing from the A.C. supply to the D.C. welding output is thus easily

accomplished/...

accomplished as described in Section 12.1.

The complete generating set with diesel driving engine will shortly be constructed and the unit will be tested in the field and its performance evaluated.

There is much scope for further work on the transient analysis of the machine to short and open circuit conditions.

This particular field of research is of great importance in the design of all types of rotating machinery. A precise knowledge of the transient and sub-transient reactances would make possible the optimum design of machines for special applications such as welding generators.

Although the thesis deals with this subject in a qualitative manner, lack of time prevented a full investigation into the quantitative aspects of the machine's transient properties from being carried out.

ACKNOWLEDGEMENTS

The author wishes to thank the following for their contributions towards this thesis:

Professor N.C. de V. Enslin for the keen interest shown in the work at all times and for his guidance and encouragement through the unrewarding stages of the research.

Mr. R.J. Waters for the initial work done on the brushless alternator in his B.Sc. Thesis. In particular for the design and construction, with the help of the Departmental Workshop Staff, of the variable low resistance artificial D.C. arc load used for all steady load tests on the generator.

Messrs. Industrial Units (Cape) (Pty) Limited, for the loan of the machines and other equipment necessary to complete the thesis.

The Staff of the Electrical Engineering Department for any help and criticism offered towards the research and the available facilities in the Department for preparing the final draft of the thesis.

16. APPENDICES

16.1 APPENDIX 1

TABLE 3.1

DERIVED CONSTANT EXCITATION CURVES AT UNITY POWER FACTOR LOAD

Field Ext 0.05 amps		Field Ext 0.11 amps		Field Ext 0.21 amps		Field Ext 0.30 amps		Field Ext 0.46 amps		Field Ext 0.60 amps		Field Ext 0.80 amps	
Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps
0	22	0	37	0	60	0	84	0	126	0	162	0	215
12.5	18	12.5	35	12.5	58	12.5	83	12.5	125	12.5	161	12.5	215
35	0	35	30	35	56	35	80	35	123	35	160	35	213
		60	0	60	48	60	76	60	122	60	158	60	212
				75	41	75	70	75	120	75	155	75	210
				100	0	100	59	100	112	100	150	100	205
						110	50	110	107	110	146	110	203
						125	0	125	95	125	138	125	197
								135	82	135	128	135	192
								150	0	150	100	150	173
										160	0	160	138
												170	0

TABLE 5.1

LOAD TEST CURVES AT UNITY POWER FACTOR LOAD - WITHOUT VOLTAGE FEEDBACK

Field Ext 0.05 amps		Field Ext 0.11 amps		Field Ext 0.21 amps		Field Ext 0.30 amps		Field Ext 0.46 amps		Field Ext 0.60 amps		Field Ext 0.80 amps	
Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps
34	0	60	0	99	0	125	0	150	0	161	0	171	0
30	7.5	54	13.0	88	21.3	118	27.6	144	35	148	69	40	205
25	12.0	44	21.2	73	35.0	100	46.3	132	61.0	71	143	28	206
18	15.6	32	28.0	54	47.3	65	69.8	90	97.2	50	151	20	206
16	16.6	24	30.5	48	50.1	40	80.0	60	112	31	156	15	207
10	18.5	16	32.5	28	56.3	20	83.0	40	120	22	158	0	210
6	19.3	10	34.0	14	58.4	12	84.5	24	123	14	159		
4	19.6	6	34.5	7	59.0	6	84.7	15	125	12	159		
2	19.8	3	34.7	5	59.5	3	85.0	9	126	0	160		
0	20.0	0	35.0	0	60.0	0	85.1	0	127				

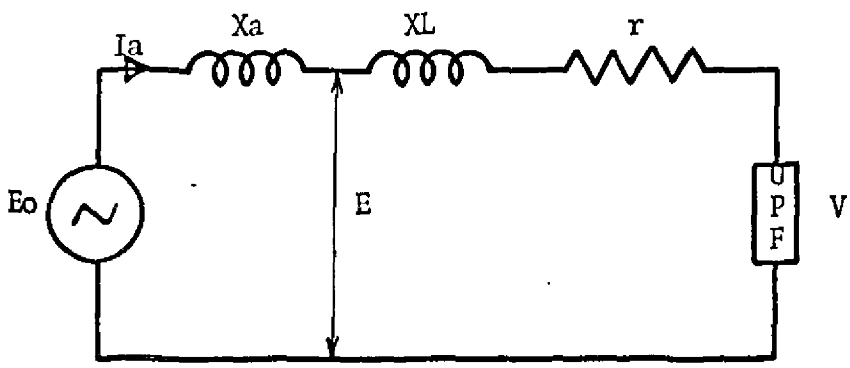
TABLE 5.2

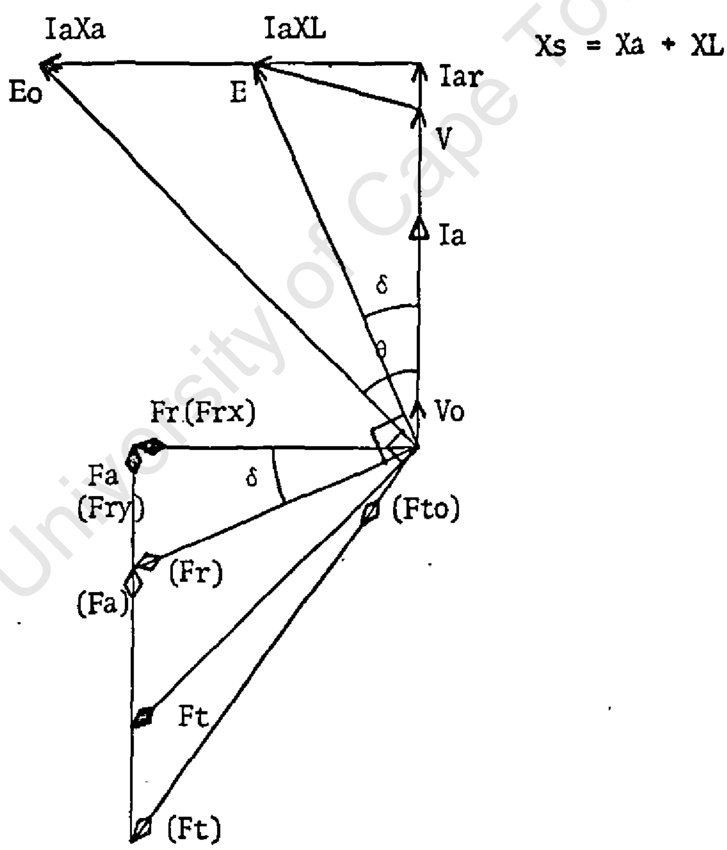
LOAD TEST CURVES AT UNITY POWER FACTOR LOAD - WITH VOLTAGE FEEDBACK

50 Volts Open Circuit (line)						70 Volts Open Circuit (line)					
S.C. Ext. .11 amps		S.C. Ext. .30 amps		S.C. Ext. .60 amps		S.C. Ext. .30 amps		S.C. Ext. .60 amps		S.C. Ext. .80 amps	
Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps	Volts	Amps
50	0	50	0	50	0	70	0	70	0	70	0
41	16	38	32	42	58	60	21	62	42	61	80
32	25	30	46	34	83	48	42	53	73	52	117
22	30	22	60	27	105	35	55	37	110	39	147
14	35	13	70	20	120	22	68	26	127	26	177
7	35.5	7	78	12	140	11	77	17	142	14	195
0	36	0	85	0	162	0	85	0	162	0	214

16.2. APPENDIX 2

COMPUTED CONSTANT EXCITATION CURVES AT UNITY POWER FACTOR LOAD





Now $(Ft + Fto)^2 = Frx^2 + (Fa + Fry)^2$ for (F-) at angle δ

$$= Frx^2 + (Fa + Frx \tan \quad)^2$$

$$= Frx^2 + \left(Fa + Frx.\frac{IaXL}{(Iar + V)}\right)^2$$

$$= Frx^2 + Fa^2 + 2\,Frx.\frac{IaXL.Fa}{(Iar+V)} + \frac{(FrxIaXL)^2}{(Iar + V)}$$

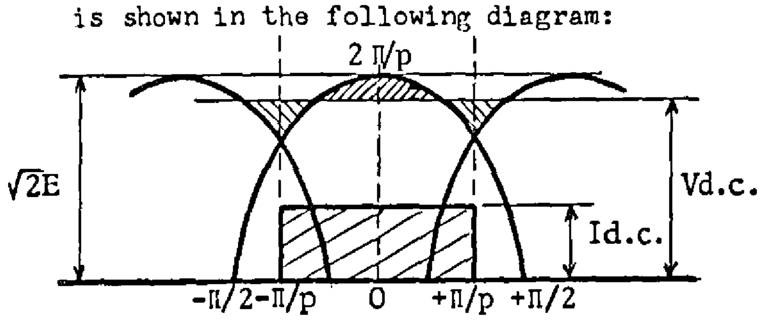
For/...

16.3 APPENDIX 3

VOLTAGE AND CURRENT RELATIONSHIPS FOR BRIDGE RECTIFIERS

16.3.1 VOLTAGE RELATIONS

For a 3-phase bridge rectifier the relation between the voltages on the A.C. and D.C. sides is shown in the following diagram:



E = R.m.s. Phase Voltage on A.C. side.

Vd.c. = Average Output Voltage on D.C. side.

p = Number of Phase Pulses.

For a theoretically perfect rectifier system each phase operates over a period of $2\pi/p$ radians. The output voltage is then the average value of a cosine waveform of amplitude $\sqrt{2}$ E between ordinates $\frac{\pi}{p}$ on either side of the maximum taken at zero time.

Thus the magnitude:

$$\begin{aligned} V_{d.c.} &= E.\ \sqrt{2}.p/2\pi \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} \cos wt.\ d(wt) \\ &= E.\ \sqrt{2}.p/\pi\ \sin\ \pi/p \end{aligned}$$

For a simple 3-phase half wave bridge rectifier, p = 3 for three diode elements.

$$\begin{aligned} \text{Then } V_{d.c.} &= E.\ \sqrt{2}.3/\ .\sqrt{3}/2 \\ &= 1.17\ E. \end{aligned}$$

As the bridge used in the welding generator set is a 3-phase full wave bridge rectifier the average D.C. output voltage will be doubled.

So Vd.c. = 2.34 E (Phase)

The/...

The voltage E is the A.C. R.m.s. phase voltage of a star connected supply with a neutral connection.

For a delta connected supply without neutral connection, taking the $\sqrt{3}$ ratio into account

$$V_{d.c.} \doteq 1.35 \ E \text{ (Line)}$$

In practice the actual voltage relation is somewhat less than the theoretical ratio due to resistive or reactive voltage drops in:

(a) the rectifying element (Watts loss/Id.c.)

(b) the connecting terminals and windings.

(c) possible current sharing reactors.

(d) commutating reactance between elements.

16.3.2 CURRENT RELATIONS

Again for the perfect rectifier, the output is a pure direct current free from distortion. This output is the sum total of successive phase currents and so each phase must have a rectangular waveform as shown in the previous diagram. The current block extends for the period of conduction of one phase, i.e. $2\pi/p$ radians.

For a 3-phase bridge rectifier with 6 elements giving full wave rectification it follows that each element conducts for 1/3 cycle and so there are always two elements conducting at any particular time. Neglecting commutation lag and overlap there is a 1/6 cycle period of common conduction

between/...

of the bridge. The main causes of distortion are:

(a) Non-sinusoidal output voltage waveforms from power source supplying the rectifier.

(b) Unsymmetrical diode characteristics in the rectifier bridge.

(c) Variable power factors on load side.

(d) Changes in the commutation angles of the diodes.

VOLTAGE AND CURRENT RELATIONS FOR A RESISTIVE LOAD

(From load tests on a 3-phase full wave bridge rectifier)

Voltage Ratio			Current Ratio		
A.C.(line) R.m.s.	D.C. Ave.	Ratio D.C./A.C	A.C.(line) R.m.s.	D.C. Ave.	Ratio A.C./D.C.
45.5	60.0	1.32	0	0	-
32.5	38.2	1.17	34.5	44	0.78
20.8	24.0	1.15	50.0	65	0.77
11.3	12.0	1.06	60.0	80	0.75
7.2	6.8	0.95	63.7	85	0.75
2.5	1.5	0.60	67.8	90	0.75
45.6	60.0	1.31	0	0	-
36.2	43.0	1.19	56.8	73	0.78
27.8	32.0	1.15	85.0	111	0.77
23.0	25.0	1.09	101	134	0.76
14.0	13.5	0.96	116	155	0.75
6.0	3.0	0.50	138	182	0.76

NOTE: (See Recs. 7.4 and 8.2)

Voltage Ratio decreases for increasing Current.

Current Ratio increases for increasing Voltage.

i.e. Waveform distortion increases with increasing Current.