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# THE INFLUENCE OF THE STATIC AND DYNAMIC CHARACTERISTICS OF POWER SOURCES ON THE BEHAVIOUR OF SHORT CIRCUITING $CO_2$ SHIELDED WELDING ARCS

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# The influence of the static and dynamic characteristics of power sources on the behaviour of short circuiting $CO_2$ shielded welding arcs

- by -

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## SUMMARY

The work discussed in this report has examined, oscillographically, the influence of variable slope and variable inductance on the characteristics of short circuiting $CO_2$ shielded metal arcs, and the variables affecting the optimum welding conditions have been determined. It has been established that this optimum is usually below the maximum of the frequency-voltage curve. Both the slope of the power source characteristic and the value of the inductance in the circuit have similar qualitative effects on the stability of the short circuiting arc. Nevertheless, control of the dynamic response by varying inductance has been found to be more flexible and effective. For this reason, it is suggested that separate control of the static characteristic and dynamic response is not necessary to obtain optimum conditions. Thus the correctly designed power source for short circuiting $CO_2$ shielded arc welding should have constant slope of the static characteristic and continuous control of the dynamic response.

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Note:- This report is based on work carried out by B. Pierozeck at Cranfield under United Nations Fellowship arrangements. Mr. Pierozeck is a member of the staff of The Institute of Welding, Gliewice, Poland.

# Contents

## Introduction

The problem of metal transfer in a gas shielded welding arc with a consumable electrode has been attracting the attention of investigators since a knowledge of the controlling factors can assist in extending the scope of the process. Improvements in control and efficiency of the welding operation and in the design of suitable power sources should follow from a better understanding of the mechanisms of metal transfer.

## Metal transfer characteristics

The mode of metal transfer which occurs with steels in the M.I.G. process can be basically of two types. Firstly, free flight (or 'spray') transfer can occur, in which case the molten droplet is detached from the electrode wire and transferred across the arc into the weld pool. The use of spray transfer, in the welding of steels, is limited to the downhand position, since the high voltages and currents necessary for this mode of transfer cause a large fluid pool to be formed which cannot be controlled in the vertical and overhead positions.

Secondly, short circuiting (or 'dip') transfer can be used in which the electrode touches the molten pool, causing a short circuit (Fig. 1a) the rise in current during the short circuiting period melts the end of the electrode and molten metal is thus transferred to the weld pool. Lower voltages and currents together with a reduction in the time during which the arc exists result in a small weld pool which freezes rapidly and can be controlled in all positions.

## Power source characteristics

In both spray and dip transfer techniques the output characteristics of the power source will have a profound effect on the ability to control the arc. For a given electrode and shielding gas, arc voltage is a function of arc current and arc length. An arc can be established between a consumable electrode and a workpiece only if the correct relationship between these variables is maintained. This implies that the power source response must be sufficiently rapid to follow any changes in voltage and current resulting from variations in arc length.

A 'spray' transfer arc operates under virtually steady conditions, only slight inflections being observed in the voltage and current traces at the instant a droplet is detached (Fig. 1b). Changes in arc length produced by movement of the welding torch or workpiece cause relatively slow variations in voltage and current which can be readily accommodated by the static characteristic of the power source which should be of the constant potential type (Fig. 2).

In the 'dip' transfer arc, on the other hand, the voltage and current drawn from the power source are constantly changing (Fig. 3). The dynamic current changes during short circuiting in this process are particularly significant. When the electrode touches down into the pool, the current rises rapidly to a peak value ($I_p$) at which point the short circuit is cleared and the current falls to a minimum value known as the standing current ($I_s$). This cycle is then recommenced with a new short circuit. The rate of current rise must be controlled since if it is too fast excessive spatter can occur, whereas if it is too slow insufficient peak current ($I_p$) is available to break the short circuit bridge and stubbing or instability can occur (Fig. 4). The current rise is exponential and is a function of the inductance of the welding circuit:-

$$I = \frac{V}{R}\left(1 - e^{-\frac{Rt}{L}}\right) \qquad \text{(i)}$$

I = current
V = voltage
L = inductance in circuit.

The peak current reached during this rise is a function of the wire diameter. Thus for dip transfer techniques the dynamic characteristics of the power source must be such that control can be exercised over the rate of rise of current. During the short circuit period, the voltage rises exponentially, primarily due to increasing $I^2R$ effects in the electrode wire extension as the current increases.

Droplet detachment during dip transfer

It has been shown by a number of workers that, for a correctly operating short circuiting arc, the arc is gradually extinguished by the advancement of the electrode tip, which has adopted a rounded profile. After the electrode tip has made contact with the weld pool, $I^2R$ heating occurs in the wire causing the metal to melt. Electromagnetic pinch and surface tension effects will cause the diameter of the wire to be reduced and the molten metal to flow into the pool, thus breaking the short circuit and re-establishing an arc gap. Two fundamental conclusions of the theory of electromagnetic pinch effects are important in the consideration of droplet detachment in dip transfer for welding. They are:-

(a) when a current carrying conductor is under the influence of its own magnetic field, radial contractile forces appear which produce pressure within the conductor, and

(b) when a conductor of a circular cross section is conic, axial forces are acting in it, being directed from the smaller cross-section to the larger and serving to detach a drop from the electrode. The pinch contraction force acting at a distance r from the axis of a liquid conductor is given by:-

$$f_m = \frac{5mI^2r^2}{2\pi^2a^4}\,(\text{Kg/cm}^2) \qquad \text{(ii)}$$

where m = magnetic permeability
I = current in conductor
a = conductor radius.

It is evident from this relationship that the value of the pinch contractile force diminishes very rapidly from the external surface to the axis of the cylindrical conductor (3). When a constriction develops under the pinch pressure the molten droplet moves with an exponential acceleration towards the arc. In other words, the magnetic pinch forces ensure the movement of the drop towards the weld pool. During this process, the kinetic energy of the drop grows. In the closed volume of the cylindrical conductor the pinch forces will produce hydrostatic pressure which must be balanced by the magnetic pinch pressure. The maximum pressure at the conductor axis due to pinch is:-

$$P_{max} = \frac{5mI^2}{\pi^2 r^2} \ (kg/cm^2) \qquad \text{(iii)}$$

The pressure distribution inside the conductor is shown in Fig. 5(3). When the conductor is molten, as in dip-transfer welding, only a small pinch force is needed to change its shape. The rate at which this force is applied governs the production of spatter during short circuiting. Since pinch is a function of current, it is apparent that both metal transfer and spatter can be controlled by regulation of current.

Smith (1,2) has found that, in dip-transfer, an important relationship exists between the frequency of short circuits and the arc voltage, showing a maximum number of short circuits at a particular voltage. He states that at this maximum, optimum welding conditions are observed and he has produced characteristic frequency-voltage curves for various electrodes with $CO_2$ shielding (Fig. 6). The frequency of short circuiting will also be influenced by wire feed rate since the rate at which the filler wire is delivered must be related to the rate at which it is melted if a stable arc is to be maintained. The latter rate is partly limited by the static characteristic of the power source and the arc length. The frequency maxima are significantly depressed and moved to a higher voltage as the wire feed rate is increased (Fig. 7).

Electrode extension influences welding current (Fig. 8) and may affect the mode of short circuiting. As the extension is increased the current decreases but the amount of $I^2R$ heating becomes greater and at long extensions the end of the electrode becomes plastic. Thus when the peak current, $I_p$, is drawn to break the short circuit a 'whipping' action is produced which results in considerably increased spatter. The effect of electrode extension on short circuit frequency is shown in Fig. 9.

## Control of metal transfer

The control of rate of rise of current, peak current and short circuiting frequency is achieved by adjustment of the dynamic response of the power source. By adding a small amount of series inductance to the welding circuit it is possible to improve the stability of the short circuiting arc process and the appearance of the resulting weld bead. The quantity of spatter produced during dip-transfer can also be controlled by the inclusion of series inductance in the circuit. The amount of inductance that can be introduced is limited, however, since the time constant of the circuit must satisfy the requirements of the repeatability of the short circuiting process. An example of the effect of increasing the time constant by adding inductance is illustrated in Fig. 10 where the short circuit frequency is plotted as a function of the number of turns in a coil included in the supply to the electrode. In general an increase in inductance results in a reduction in peak current, $I_p$, rate of current rise, and short circuit frequency.

As an alternative to the addition of inductance, it is possible to control the rate of rise of current by varying the 'slope' of the output characteristic of the power source. In this case the output voltage is allowed to fall as the current being drawn rises and an increase in slope produces a similar effect to the inclusion of more inductance.

In current practice, when establishing a suitable arc condition for welding, the voltage is first set to give a maximum number of short circuits and the circuit is then adjusted by variation of inductance or slope, to give the most satisfactory mode of metal transfer consistent with low spatter loss. Smith (2) has recommended optimum operating conditions for a range of electrode sizes. These are summarised in Table 1.

## Present work

From what has been said above, it can be seen that a number of factors must be controlled to achieve optimum welding conditions for dip-transfer techniques. It is not possible to separate all the factors taking part in metal transfer and little data on the quantitative effects of the various parameters is available. Which of these exerts the most significant effect on arc stability and spatter production has yet to be established conclusively.

At present, two welding systems are in general use:-

(a) a constant potential power source having variable open circuit voltage, with variable or fixed series conductance, and

(b) a variable slope source, having variable open circuit voltage, but without series inductance.

Both these systems provide adequate control of the arc and the choice between them is difficult. It is the object of the work described in this report to compare the two types of equipment by examining their relative abilities to control the rate of rise of current, peak current and short circuit frequency during dip-transfer welding.

## Experimental work

### Equipment

The layout of welding equipment and test apparatus used in the investigations is shown in Fig. 11.

#### (a) Welding head

A thyratron controlled variable speed motor, capable of giving wire feed speeds between 50 and 250 in/min, was mounted above a water cooled torch. Water, gas and power were supplied direct to the torch.

#### (b) Power source

Two power sources were used. Power source 'A' was a constant potential rectifier with open circuit voltage infinitely variable from 14 - 44 volts. The maximum continuous current rating was 500 amp. and the output characteristic had a slope of 3 volt/100 amp. (Fig. 12).

Power source 'B' was a selenium type rectifier with continuously variable voltage and slope. The output from this unit was up to 200 amp. (continuous) at between 10 and 40 volts. The slope of the output could be varied from 2 volt/100 amp. to 8 volt/100 amp. (Fig. 13).

#### (c) Inductance

Two coupled inductances, rated for use up to 300 amps were inserted in the welding circuit. By varying the connections between the coils four values of inductance could be achieved (Fig. 14).

#### (d) Recording equipment

Records of voltage and current were made on a Siemens Oscillomink, direct writing oscillographic recorder (Fig. 15). This unit contained two amplifiers feeding two loop galvanometers. An un-amplified 50 cycle/sec. alternating voltage was supplied to a third galvanometer to facilitate the measurement of time intervals. Chart speeds from 0.5 cm/sec. to 200 cm/sec. were available. The input impedance of the amplifiers was 1 megohm and the maximum sensitivity was 10 m.m./50 mV.

#### (e) Electrode

An electrode wire of $^{3}/_{64}$ in. diameter was chosen since this size may be used for welding over a wide current range, being suitable for short circuiting down to 80 amp. and 'spray' transfer up to about 400 amps. The composition of this wire is given in Table 2.

## Experimental procedure

The self-adjusting welding head was used to deposit weld beads on $2\frac{1}{2}$ in. diameter tube samples under carefully controlled conditions. During the tests the current, voltage, wire feed rate and welding speed were recorded. The voltage was measured between the electrode wire and the workpiece. Although the arc voltage is regarded as one of the most important variables in this work, it cannot be easily measured. With the power sources used in this work, however, the open circuit voltage can be taken as the independent variable and all the graphs are plotted against this value. Arc voltage, as generally understood in welding, is therefore somewhat lower than the figures reported here; the exact difference will depend on the output characteristic of the power source.

Slow speed oscillograms (10 cm/sec) were used in the measurement of transients in current and voltage waveforms. Data taken from the oscillographic traces has been given as the arithmetical mean of a number of short circuit cycles.

The majority of the tests were made with Power Source 'B' and a wire feed speed of 100 in/min. Repeatability checks were made with Power Source 'A' using 75 in/min wire feed rate. In the latter case, variation in the slope of the output characteristic was obtained by the addition of pure resistance in the welding circuit. Unless stated otherwise, the following variables were standardised:-

| | | |
|---|---|---|
| a. | electrode extension | $\frac{1}{2}$ in. |
| b. | welding speed | 25 in/min. |
| c. | torch angle | vertical |
| d. | nozzle diameter | $^5/_8$ in. |

For each test weld, the open circuit voltage and wire feed rate were first measured. The weld was then started and, after the weld pool was established and the arc was stable, two oscillograms were made at chart speeds of 10 cm/sec. and 50 or 100 cm/sec. These were subsequently analysed to give:-

a) short circuit frequency
b) average current rise during short circuit
c) average peak current
d) average standing current.

## Results

### Short circuit frequency

The relationships between short circuit frequency and open circuit voltage for different slopes of the static output characteristic of Power Sources 'A' and 'B' are shown in Figs. 16 and 17. For each slope used the maximum frequency was at the same voltage, i.e. 18/19 volts, but an increase in the slope lowers the short circuit frequency. Typical oscillograms, taken at maximum frequency, for corresponding current waveforms are shown in Fig. 18 and the influence of increasing value of inductance on the character of the frequency-voltage curves for constant slope is illustrated in Figs. 19 to 24. It will be seen that the shapes and maxima of these curves were similar to those obtained with varying slope. The maxima also occurred at 18/19 volts irrespective of the inductance being used.

During welding, with a wire speed of 100 in/min, it was observed (Fig. 25) that standing current varied from 120 amp with high inductance to 90 amp at lower values of inductance. The influence of changing voltage on the current and voltage wave forms during short circuit welding is demonstrated in the oscillograms in Fig. 26.

### Current rise during short circuit

Figs. 27 and 28 show the influence of variable slope and the dynamic response of the power sources on average current rise. Oscillograms from tests with the corresponding variables, slope and inductance are reproduced in Figs. 18 and 25 and data taken from these traces is tabulated in Tables 3 - 6. From the analysis of oscillograms it is apparent that the influence of both variables, slope and inductance, is qualitatively similar.

## Discussion

This investigation of the $CO_2$ shielded short circuit arc has revealed a number of interesting features. As a result of observations made during these tests, and the analysis of the oscillograms, it is suggested that the optimum welding condition is usually just below the maximum of the frequency-voltage curve, for a given wire feed rate. At this setting metal transfer is more uniform and the arc is smoother. Further, at lower short circuit frequencies the rate of current rise is somewhat slower and, if this is not below permissible levels, excessively high current peaks, which cause spatter and poor bead shape, will be avoided. In this condition, the current peaks show a more simple transition from the smooth rising exponential curve to the decay current.

The oscillograms show that changes in inductance have greater effect on the level of standing current than variations in slope. The standing current is especially important since it influences heat input during welding. The ability to control this current reduces the chance of lack of fusion faults in multi-pass welds. Normally the lack of fusion is reduced by changing the wire diameter. It seems clear, therefore, that the control of inductance in the welding circuit is much more important than adjustment of the slope if flexible and adequate control is to be achieved of the following variables:-

a) the amount of spatter
b) the short circuit frequency
c) the rate of current rise
d) the peak current
e) the standing current.

Whilst increasing the slope has a similar influence on the metal transfer characteristics, its influence is more limited, because increasing the slope partly reduces the rate of self adjustment of the arc.

Having established sufficient qualitative correlation between the metal transfer characteristics, the slope of the static characteristics and the dynamic response of the power source, it is possible to discuss whether separate control of both these variables is necessary. Recently different systems have been used to control the arc stability and the amount of spatter. Some manufacturers use fixed inductance in the welding circuit and controlling only the slope. On the other hand some use a constant slope of the output characteristic and continuously vary the inductance. Manz (4) argues that there is a need for the separation and control of both static characteristic and dynamic response in order to obtain the best welding condition. He suggests that adjustment of the static characteristics will provide the correct amount of pinch force, whilst the control of the dynamic response of the power source will provide the correct rate of pinch force variation and this combined influence should give the best results. This opinion seems to be only partly true, as it is shown by the results of this work (Tables 3-6 and included oscillograms) that the dynamic response influences equally the rate and amount of pinch force by controlling the peak current and the rate of current rise. Having thus confirmed that the effect of the dynamic response on the short circuit characteristics is more significant than that of variation of slope, it would appear that variable inductance offers better opportunities for fine control of the arc.

## Conclusions

1. The optimum welding condition during $CO_2$ shielded 'dip' transfer welding is usually slightly below the setting that gives the maximum number of short circuits per second for a given wire feed rate.

2. Variable slope and inductance have similar qualitative effects on the short circuiting characteristics.

3. Variation in inductance is more significant than variation in slope when considering control of spatter and standing current. Moreover, changing the slope may have a deleterious effect on the self-adjustment of the arc.

4. There is no need for separation and control of both the static characteristics and the dynamic response of the power source.

References

| | | |
|---|---|---|
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| 2. | Smith, A.A. | $CO_2$-shielded consumable electrode arc welding, B.W.R.A., 1962. |
| 3. | Serdiuk, G.B. | Physic of the welding arc, 1962. |
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Table 1

Optimum operating conditions for dip transfer welding (after Smith (2))

| Electrode diameter (in.) | 1/32 | 3/64 | 1/16 |
|---|---|---|---|
| Wire feed rate (in/min) | 200 | 100 | 75 |
| Operating voltage (volt) | 18 | 19 | 20 |
| Average current (amp) | 90 | 100 | 150 |
| Response rate (kA/sec) | 200 | 150 | 130 |
| Optimum value of inductance* (milli henry) | 0.01 - 0.08 | 0.01 - 0.16 | 0.30 - 0.7 |

* calculated from V = IZ, when $Z = \sqrt{R^2 + w^2L^2}$

Table 2

Chemical composition of electrode

| Element | Carbon | Silicon | Manganese |
|---|---|---|---|
| Composition % | 0.1 | 0.40 | 1.50 |

## Table 3

Data from tests with variable slope without added inductance

| | | | | | | |
|---|---|---|---|---|---|---|
| Slope No. | 0 | 2 | 4 | 6 | 8 | 10 |
| Av. slope V/100A | 2 | 3 | 4 | 5 | 6 | 8 |
| Open circuit voltage, volts | 19 | 19 | 19 | 19 | 19 | 19 |
| Av. short cct. frequency No/sec | 105 | 120 | 82 | 77 | 65 | 48 |
| Av. peak current, $I_p$ amp. | 410 | 370 | 320 | 310 | 300 | 280 |
| Max. peak current, amp. | 560 | 470 | 390 | 390 | 380 | 380 |
| Min. peak current, amp. | 300 | 280 | 220 | 180 | 180 | 200 |
| Av. standing current, $I_S$, amp. | 110 | 100 | 95 | 95 | 90 | 90 |
| Av. current rise, kA/sec. | 320 | 240 | 156 | 110 | 100 | 72 |
| Av. short circuit time, sec. | 0.001 | 0.0015 | 0.002 | 0.002 | 0.003 | 0.004 |
| Av. arc time, sec. | 0.006 | 0.005 | 0.007 | 0.007 | 0.009 | 0.007 |

Power source:- B Wire feed rate:- 100 in/min.
Wire diameter:- $^3/_{64}$ in.

# Table 4

## Data from tests with variable inductance and constant slope

| Inductance | None | | | $L_{PB}$ | | | $L_{SB}$ | | | $L_P$ | | | $L_S$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Slope | 0 | 4 | 10 | 0 | 4 | 10 | 0 | 4 | 10 | 0 | 4 | 10 | 0 | 4 | 10 |
| Open circuit voltage, volts | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| Av. short circuit frequency No/sec. | 105 | 82 | 78 | 122 | 88 | 64 | 102 | 86 | 60 | 50 | 40 | 30 | 38 | 36 | 30 |
| Av. peak current $I_p$, amp. | 410 | 320 | 280 | 290 | 290 | 260 | 180 | 160 | 160 | 270 | 260 | 280 | 260 | 240 | 240 |
| Max. peak current, amp. | 560 | 360 | 380 | 340 | 330 | 300 | 270 | 190 | 240 | 300 | 300 | 290 | 400 | 340 | 320 |
| Min. peak current, amp. | 300 | 220 | 200 | 210 | 200 | 200 | 160 | 130 | 130 | 160 | 160 | 210 | 220 | 170 | 200 |
| Av. standing current, amp. | 110 | 95 | 90 | 80 | 80 | 75 | 70 | 70 | 70 | 100 | 95 | 90 | 140 | 135 | 120 |
| Av. current rise kA/sec. | 320 | 156 | 72 | 133 | 82 | 52 | 62 | 48 | 32 | 25 | 24 | 17.2 | 20.5 | 16.8 | 14.2 |
| Av. short circuit time, sec. | .001 | .002 | .004 | .002 | .004 | .005 | .003 | .003 | .005 | .01 | .01 | .015 | .01 | .014 | .013 |
| Av. arc time, sec. | .005 | .007 | .007 | .005 | .006 | .009 | .006 | .007 | .009 | .025 | .025 | .09 | .015 | .015 | .019 |

Power Source:- 'B'　　Wire diameter:- $^3/_{64}$ in.　　Wire feed rate:- 100 in/min.

Relative additional inductance:- $L_{PB}$: $L_{SB}$: $L_p$: $L_s$:: 3.7: 15: 25: 100

### Table 5

Data from tests with variable slope and constant inductance

| Slope No. | S | $S_1$ | $S_2$ |
|---|---|---|---|
| Av. slope $^V/100A$ | 3 | 4 | 5 |
| Open circuit voltage, volts | 19 | 19 | 19 |
| Av. short cct. frequency, $^{No}/sec.$ | 55 | 66 | 62 |
| Av. peak current, $I_p$, amps. | 230 | 220 | 210 |
| Max. peak current, amp. | 300 | 280 | 300 |
| Min. peak current, amp. | 160 | 160 | 150 |
| Av. standing current, $I_s$, amp. | 50 | 55 | 50 |
| Av. current rise, kA/sec. | 32.8 | 30.0 | 30.8 |
| Av. short cct. time, sec. | 0.007 | 0.008 | 0.007 |
| Av. arc time, sec. | 0.014 | 0.008 | 0.01 |

Power source:- 'A' plus series resistance      Wire diameter:- $^3/_{64}$

Inductance:- $L_p$      Wire feed rate:- 75 in/min.

### Table 6

Data from tests with variable inductance and constant slope.

| Inductance | None | | | $L_p$ | | | $L_s$ | | |
|---|---|---|---|---|---|---|---|---|---|
| Slope No. | S | $S_1$ | $S_2$ | S | $S_1$ | $S_2$ | S | $S_1$ | $S_2$ |
| Av. slope $^V/100A$ | 3 | 4 | 5 | 3 | 4 | 5 | 3 | 4 | 5 |
| Open circuit voltage, volts | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 | 19 |
| Av. short cct. frequency, $^{No}/sec.$ | 82 | 70 | 66 | 55 | 66 | 62 | 70 | 57 | 50 |
| Av. peak current, $I_p$, amp. | 500 | 400 | 400 | 230 | 220 | 210 | 150 | 140 | 160 |
| Max. peak current, amp. | 640 | 470 | 480 | 300 | 280 | 300 | 180 | 200 | 240 |
| Min. peak current, amp. | 260 | 240 | 200 | 160 | 160 | 150 | 140 | 130 | 150 |
| Av. standing current, amp. | - | - | - | 50 | 55 | 50 | 80 | 70 | 80 |
| Av. current rise kA/sec. | 500 | 410 | 380 | 32.8 | 30.0 | 30.8 | 9.0 | 8.4 | 9.0 |
| Av. short cct. time, sec. | .001 | .0008 | | .007 | .008 | .007 | .002 | .002 | .002 |
| Av. arc time, sec. | - | .014 | - | .014 | .008 | .01 | .017 | .016 | .015 |

Power source:- 'A' + series resistance      Wire diameter:- $^3/_{64}$ in.

Relative inductance:- $L_p$:$L_s$::25:100      Wire feed rate:- 75 in/min.

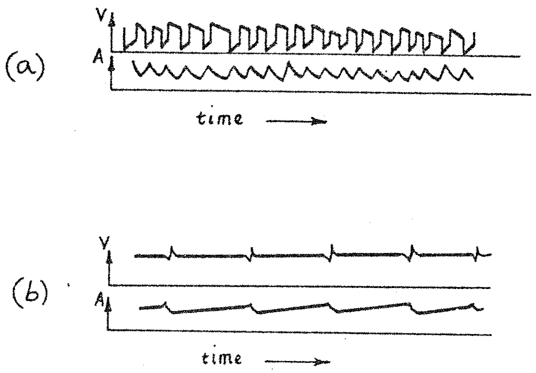

FIGURE 1 TYPICAL OSCILLOGRAMS SHOWING VOLTAGE AND CURRENT WAVEFORMS FOR (a) DIP TRANSFER AND (b) SPRAY TRANSFER

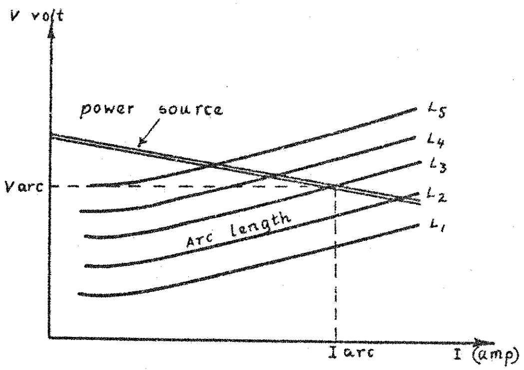

FIGURE 2 INTERACTION BETWEEN ARC AND POWER SOURCE STATIC CHARACTERISTICS

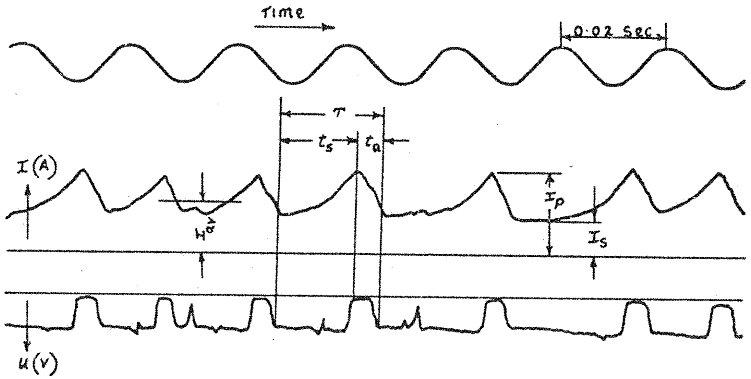

FIGURE 3 TYPICAL OSCILLOGRAM FOR "DIP" TRANSFER SYSTEMS

KEY:- T = TOTAL TIME OF CYCLE

$t_s$ = TIME OF SHORT CIRCUIT

$t_a$ = TIME OF ARCING PERIOD

$I_{av}$ = AVERAGE CURRENT

$I_p$ = PEAK CURRENT

$I_s$ = STANDING CURRENT

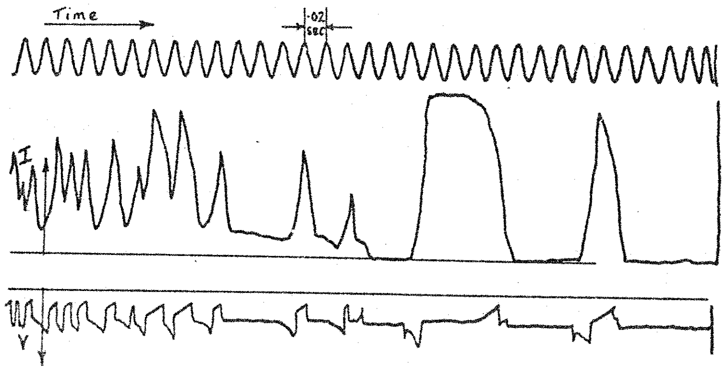

FIGURE 4 AN EXAMPLE OF AN OSCILLOGRAM SHOWING ARC INSTABILITY WITH STUBBING

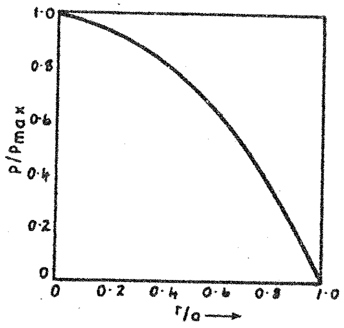

FIGURE 5 PRESSURE DISTRIBUTION INSIDE A CYLINDRICAL CONDUCTOR (AFTER SERDIUK (3))

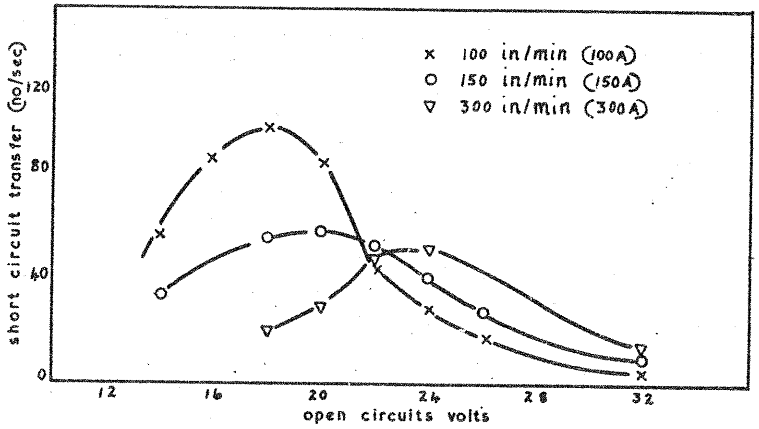

FIGURE 7 EFFECT OF INCREASING WIRE FEED RATE ON SHAPE OF FREQUENCY-VOLTAGE CURVES FOR 3/64 DIAMETER WIRE (AFTER SMITH(1))

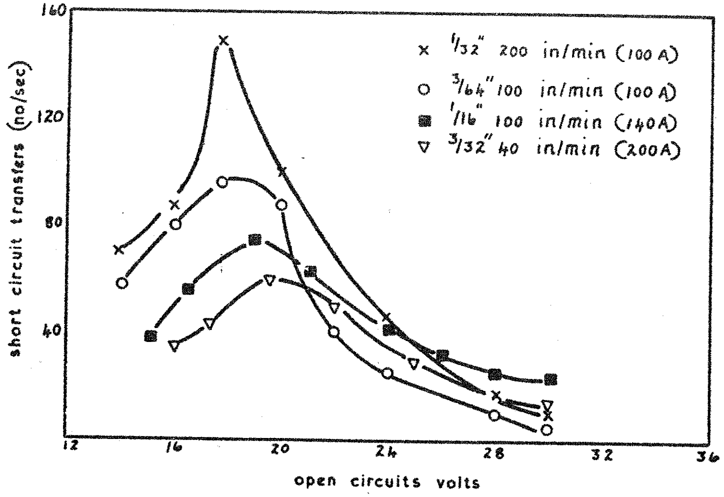

FIGURE 6 FREQUENCY-VOLTAGE CURVES FOR $CO_2$ SHIELDED WELDING WITH VARIOUS WIRE DIAMETERS (AFTER SMITH (1)).

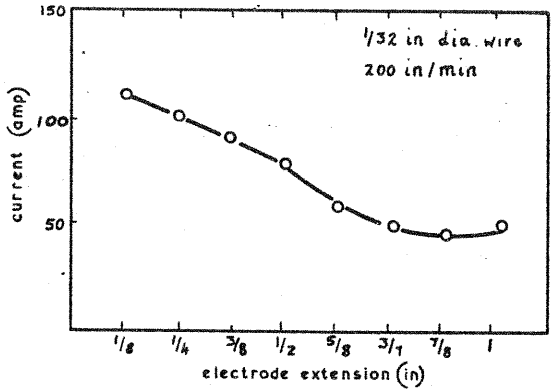

FIGURE 8 CHANGE OF CURRENT WITH INCREASING ELECTRODE EXTENSION (AFTER SMITH (1))

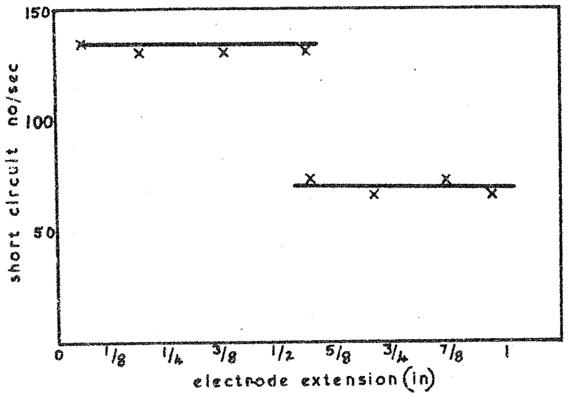

FIGURE 9 EFFECT OF INCREASING ELECTRODE EXTENSION ON SHORT CIRCUIT FREQUENCY (AFTER SMITH (1))

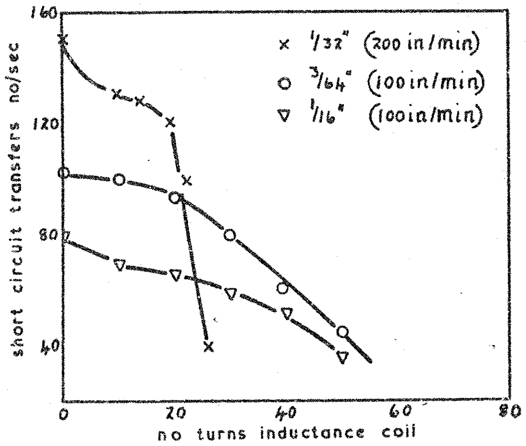

FIGURE 10 SHORT CIRCUIT FREQUENCIES FOR THREE WIRE DIAMETERS, WITH INCREASING INDUCTANCE (AFTER SMITH (1))

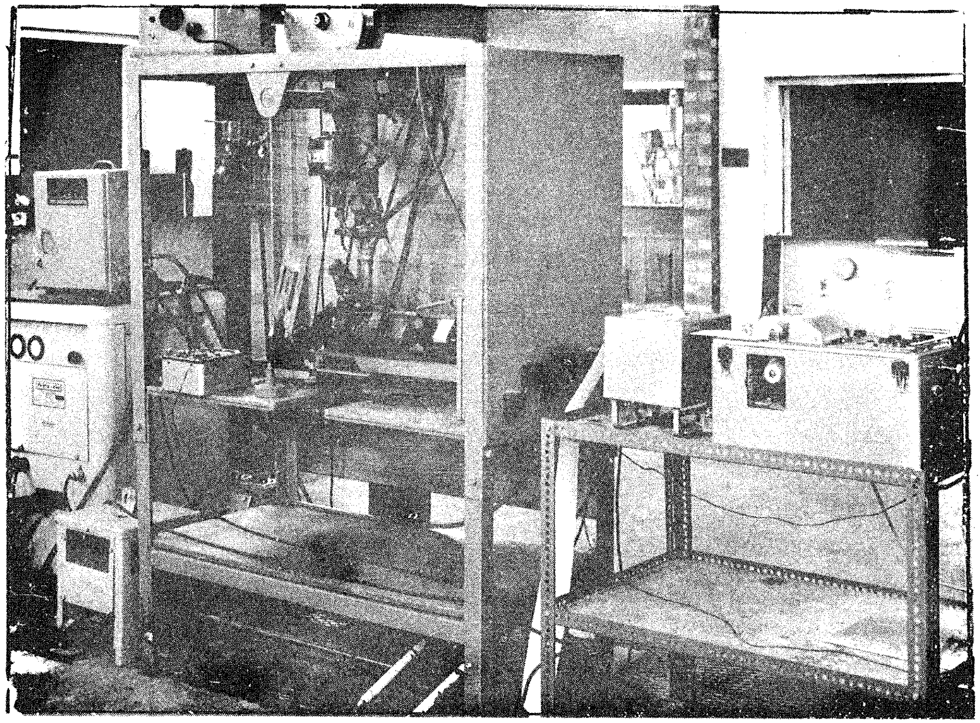

FIGURE 11 TEST APPARATUS SHOWING POWER SOURCE "A", WELDING HEAD AND OSCILLOGRAPHIC RECORDER.

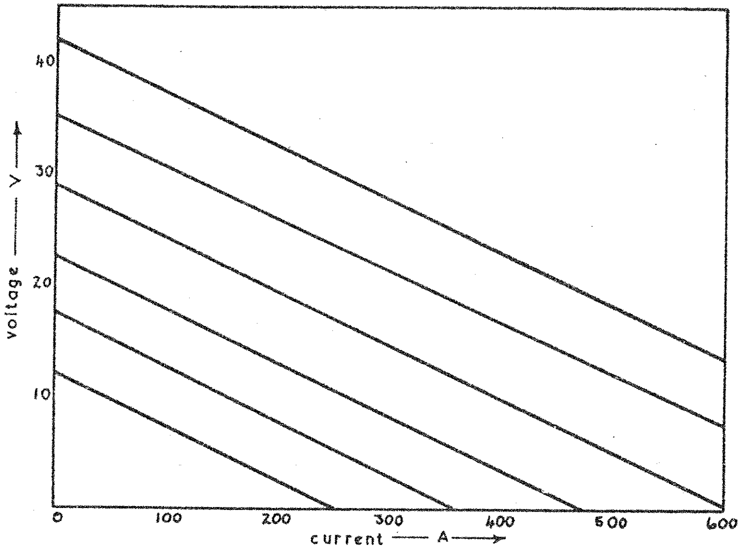

FIGURE 12 VOLT-AMPERE, STATIC CHARACTERISTICS FOR POWER SOURCE "A"

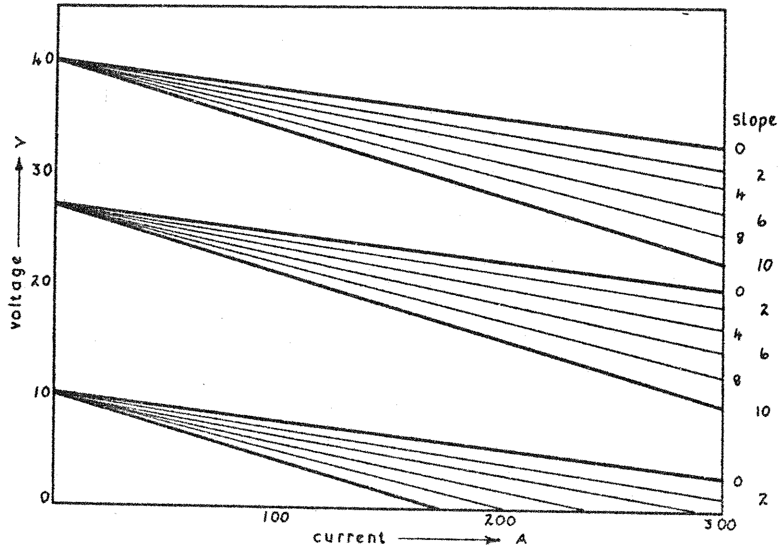

FIGURE 13 VOLT-AMPERE, STATIC CHARACTERISTICS FOR POWER SOURCE "B"

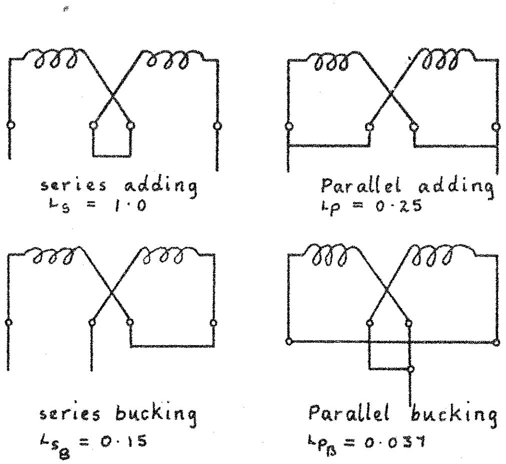

FIGURE 14 SCHEMATIC DIAGRAM OF POSSIBLE METHODS OF CONNECTING THE TWO COUPLED INDUCTANCES. (INDUCTANCE IS GIVEN IN RELATIVE VALUES)

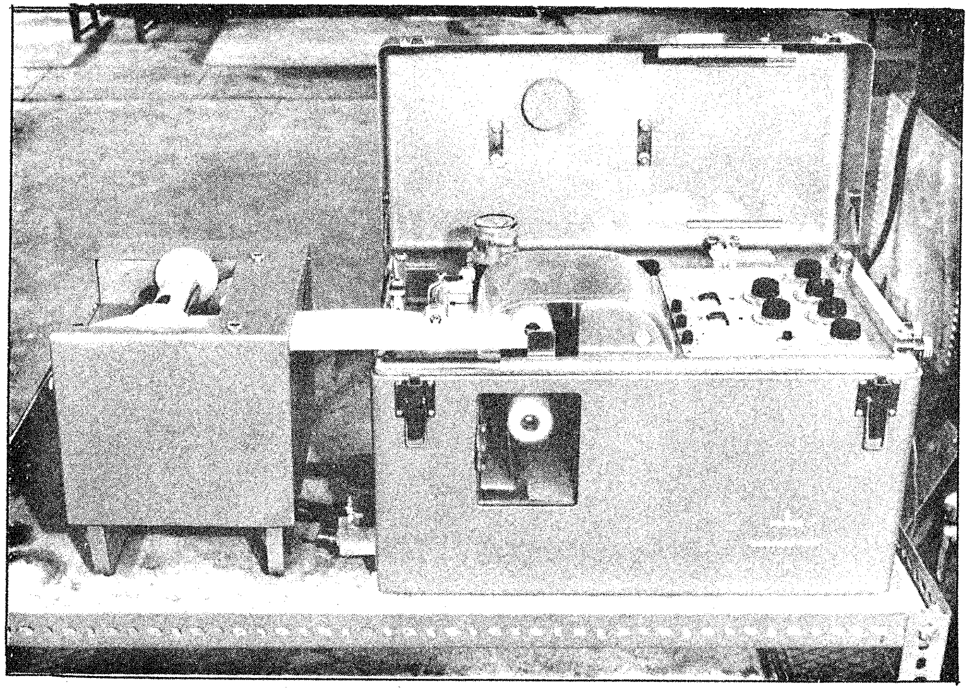

FIGURE 15 DIRECT WRITING, OSCILLOGRAPHIC RECORDER, USED TO RECORD CURRENT AND VOLTAGE DURING WELDING.

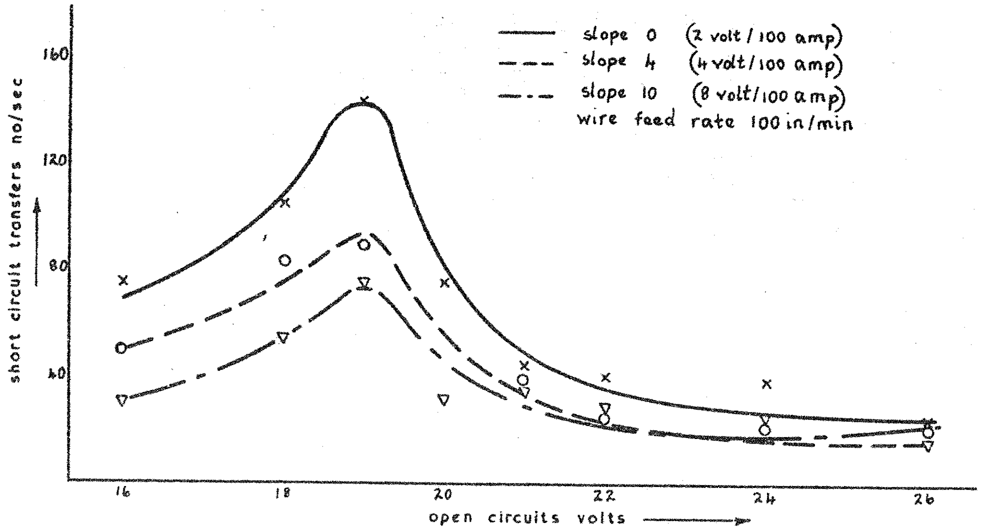

FIGURE 16 F-V CURVES FOR INCREASING SLOPE OF STATIC OUTPUT CHARACTERISTICS OF POWER SOURCE "B"

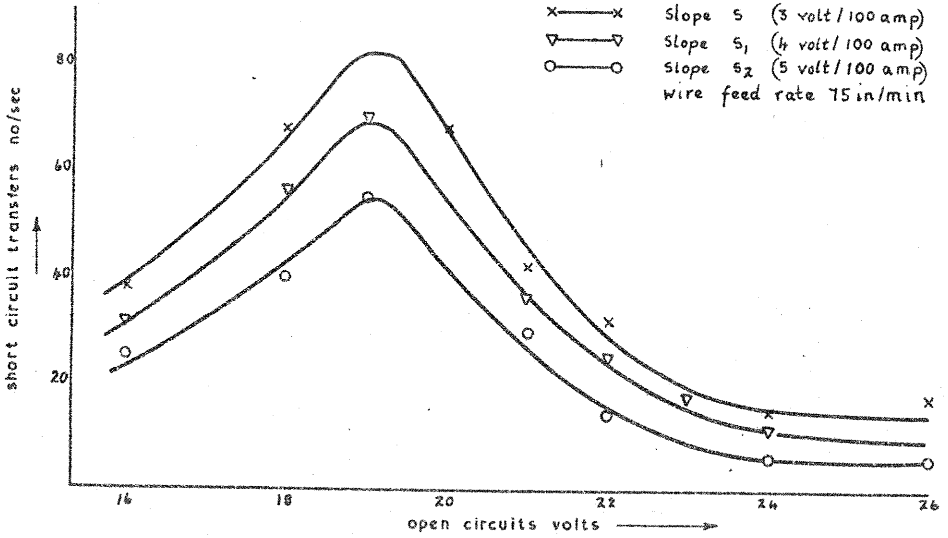

FIGURE 17 F-V CURVES FOR INCREASING SLOPE OF STATIC OUTPUT CHARACTERISTICS OF POWER SOURCE "A"

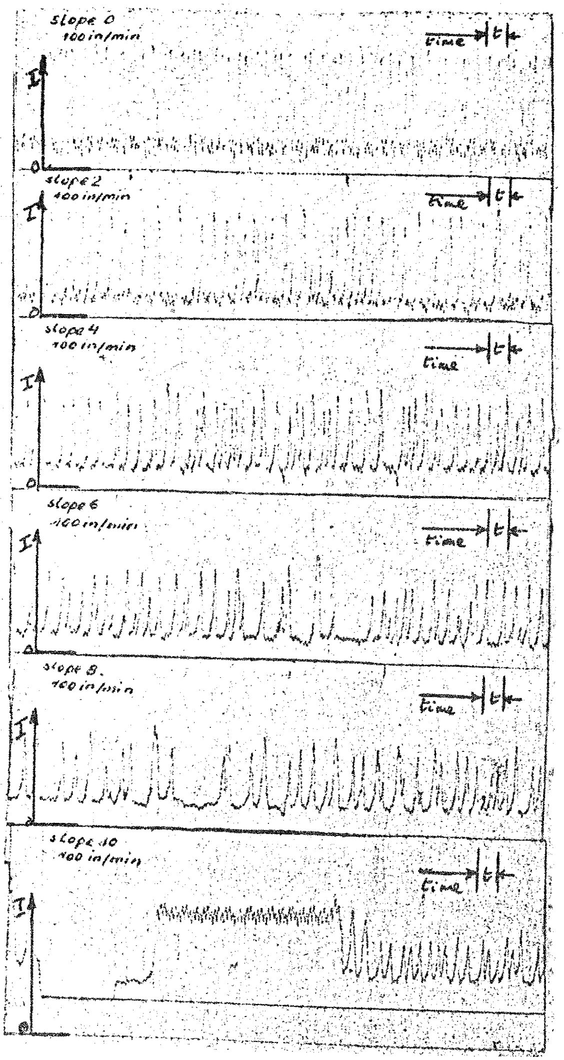

FIGURE 18 VARIATION OF CURRENT WAVEFORM WITH INCREASING SLOPE POWER SOURCE "B", OPEN CIRCUIT VOLTAGE: 19 VOLTS t = 0.02 SECS.

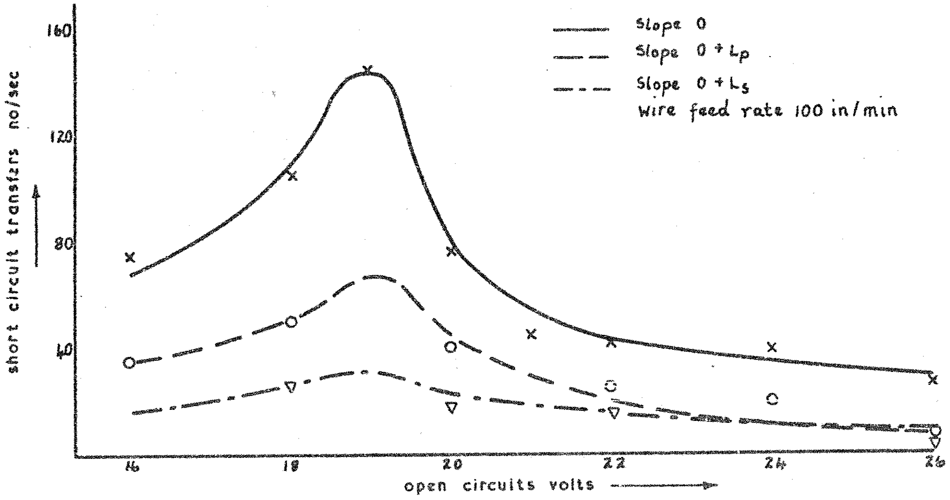

FIGURE 19 F-V CURVES FOR INCREASING DYNAMIC RESPONSE OF POWER SOURCE "B" AT SLOPE "O" (2 VOLT/100 AMP)

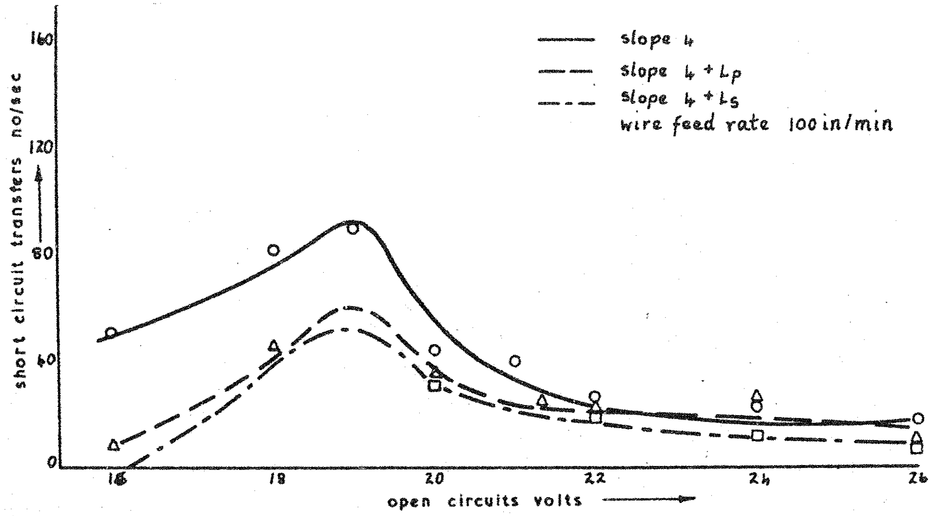

FIGURE 20 F-V CURVES FOR INCREASING DYNAMIC RESPONSE OF POWER SOURCE "B" AT SLOPE "4" (4 VOLT/100 AMP)

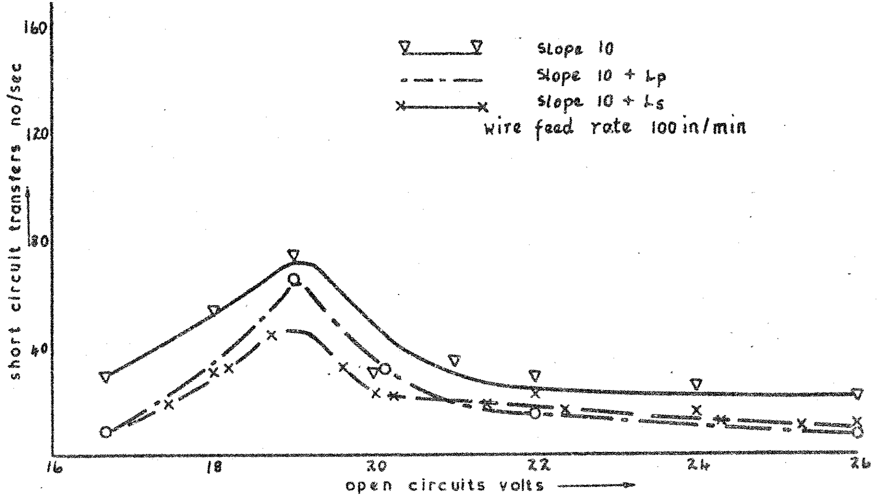

FIGURE 21 F-V CURVES FOR INCREASING DYNAMIC RESPONSE OF POWER SOURCE "B" AT SLOPE "10" (8 VOLT/100 AMP)

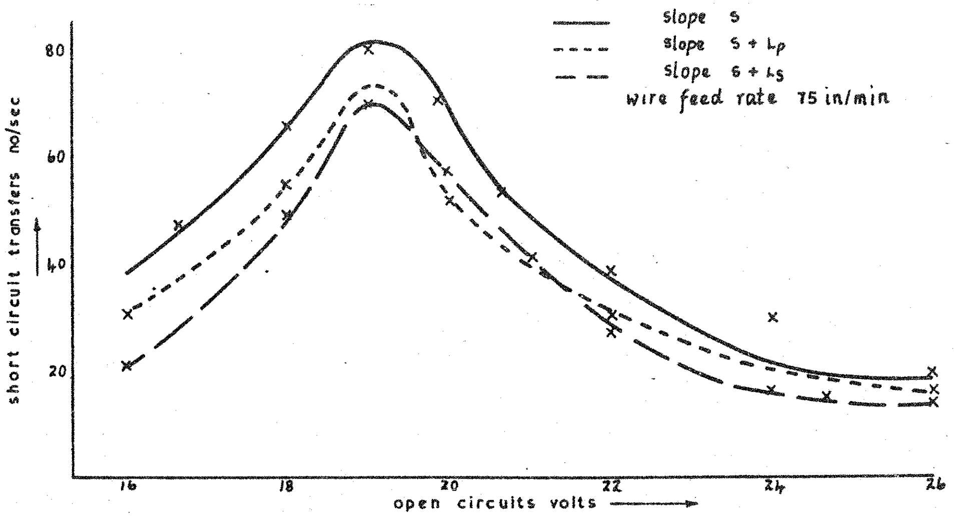

FIGURE 22 F-V CURVES FOR INCREASING DYNAMIC RESPONSE OF POWER SOURCE "A" WITH SLOPE S (3 VOLT/100 AMP)

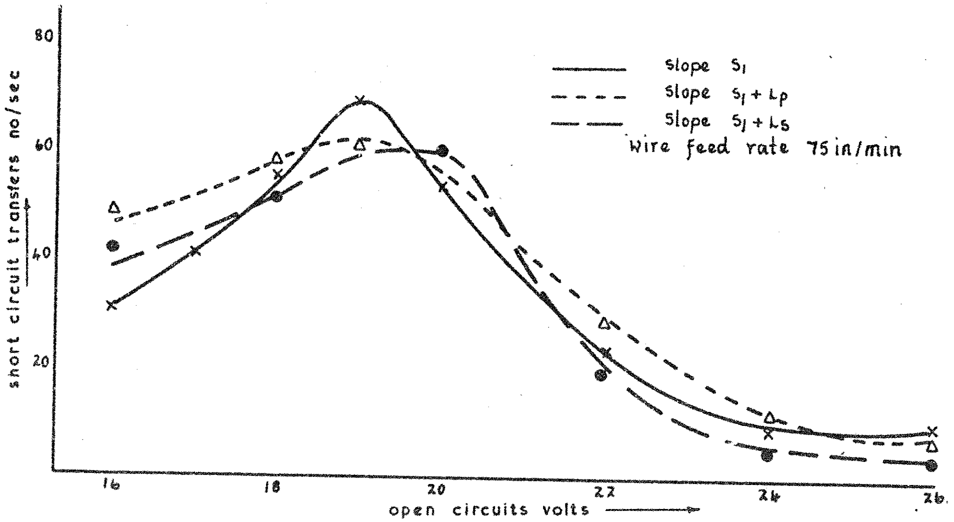

FIGURE 23 F-V CURVES FOR INCREASING DYNAMIC RESPONSE FOR POWER SOURCE "A" WITH SLOPE "$S_1$" (4 VOLT/100 AMP).

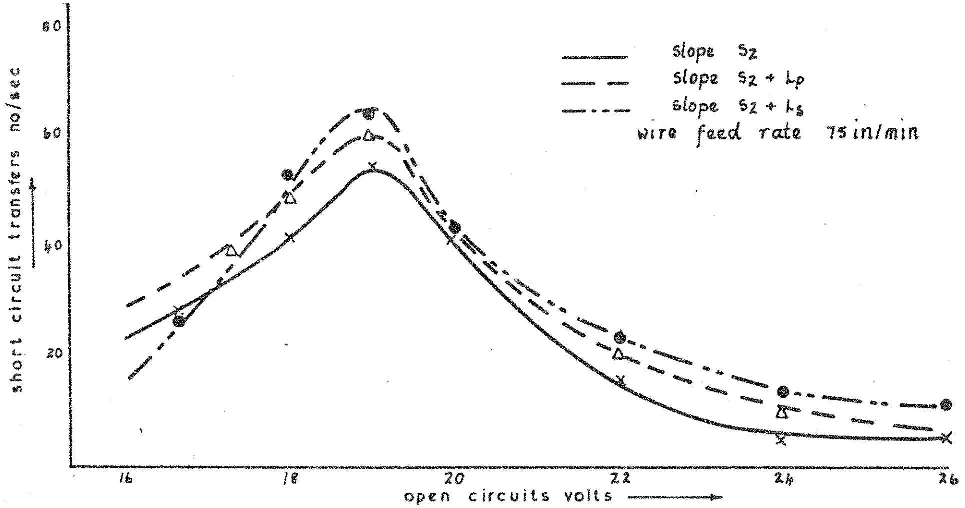

FIGURE 24 F-V CURVES FOR INCREASING DYNAMIC RESPONSE OF POWER SOURCE "A" WITH SLOPE "S2" (5 VOLT/100 AMP).

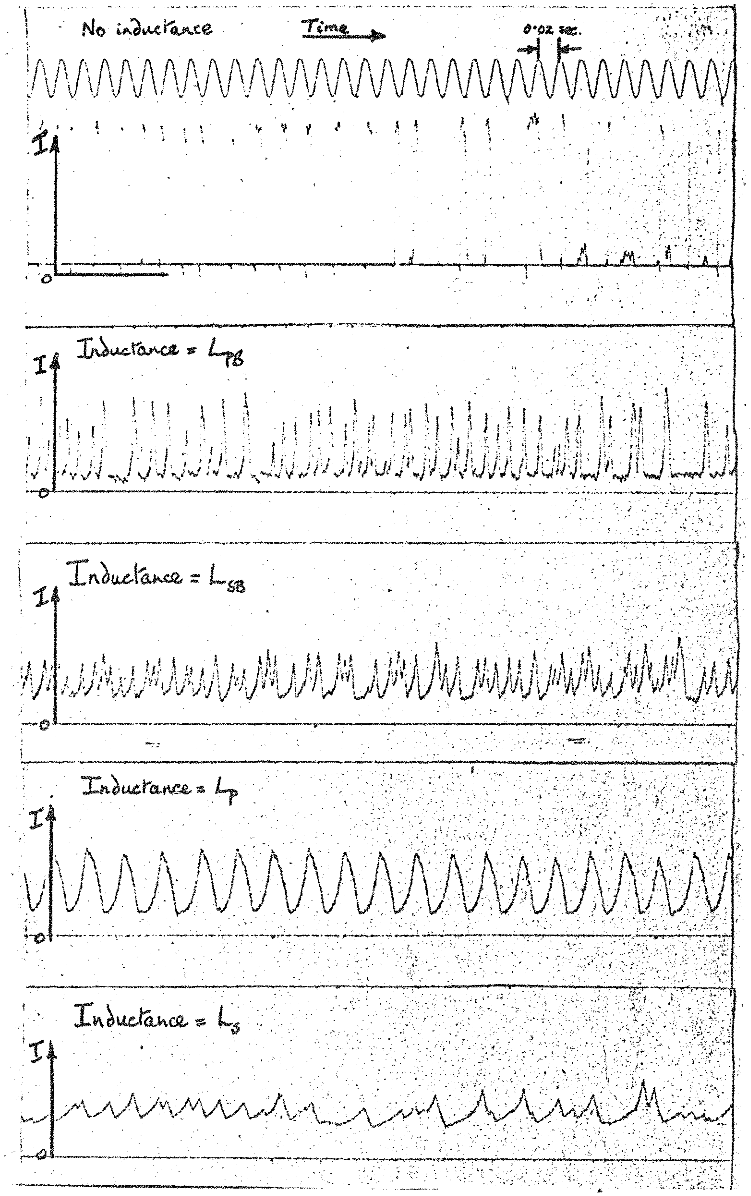

FIGURE 25 CURRENT WAVEFORMS WITH INCREASING INDUCTANCE FOR POWER SOURCE 'B' WITH SLOPE 4 (4 VOLT/100 AMP).

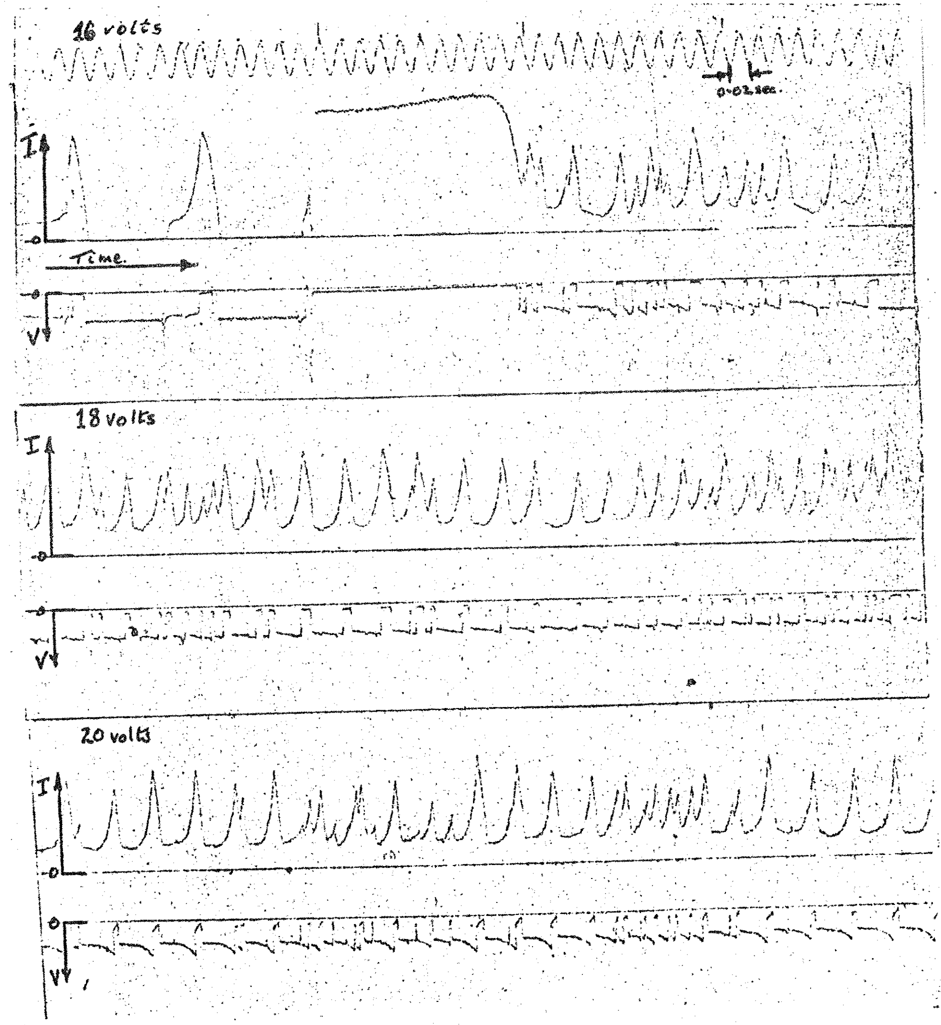

FIGURE 26(a) TYPICAL VOLTAGE AND CURRENT WAVEFORMS AT OPEN CIRCUIT VOLTAGES OF 16, 18 AND 20 VOLTS. POWER SOURCE "B" WITH INDUCTANCE $L_p$.

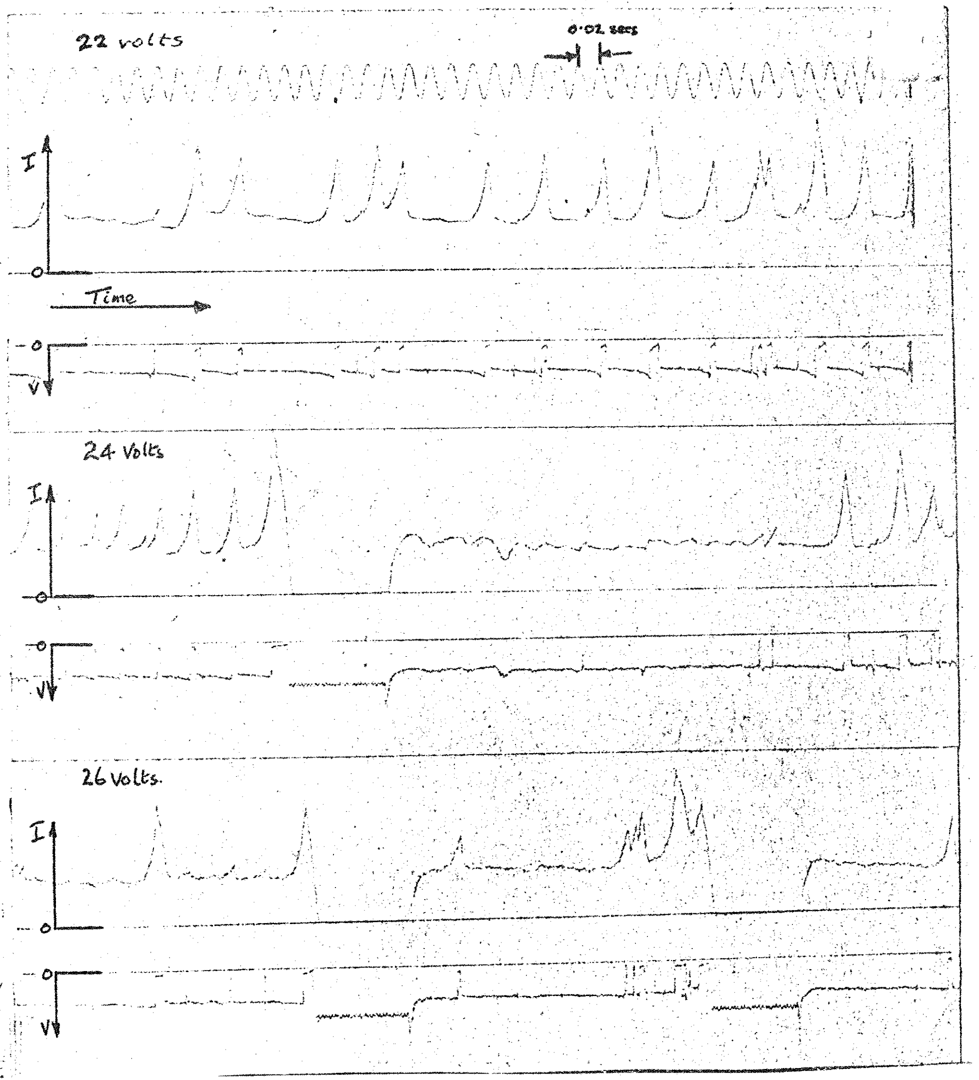

FIGURE 26(b) TYPICAL VOLTAGE AND CURRENT WAVEFORMS AT OPEN CIRCUIT VOLTAGES OF 22, 24 and 26 VOLTS. POWER SOURCE "B" WITH INDUCTANCE $L_p$.

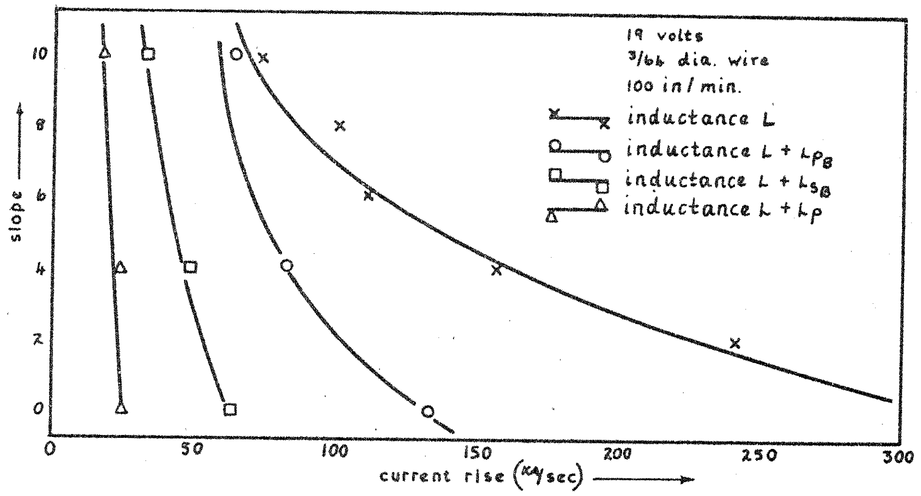

FIGURE 27 THE INFLUENCE OF CHANGE OF SLOPE ON AVERAGE CURRENT RISE FOR POWER SOURCE "B"

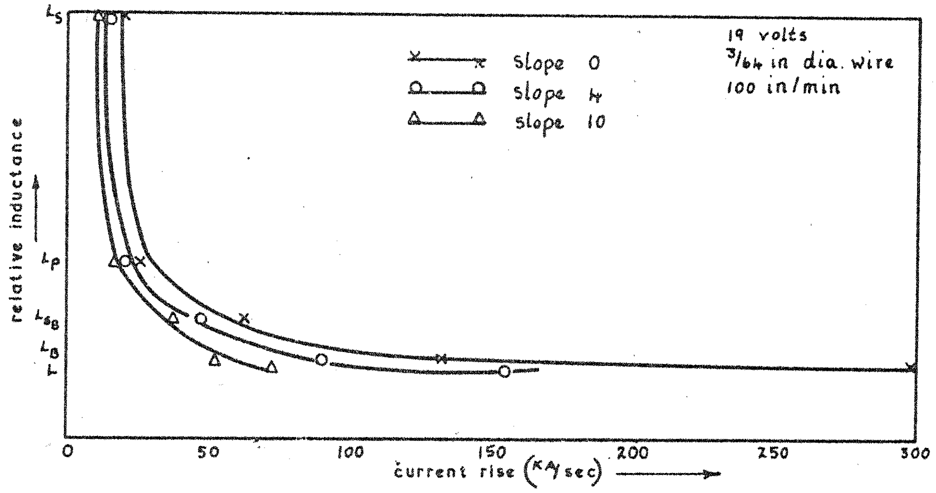

FIGURE 28 THE INFLUENCE OF CHANGE OF SLOPE ON AVERAGE CURRENT RISE FOR POWER SOURCE "B"