REFERENCES

1. KUO, B.C., "Automatic Control Systems" Prentice-Hall, Inc., 1962

2. KUO, B.C., "Analysis and Synthesis of Sampled-Data Control Systems "Prentice-Hall, Inc., 1963

3. JACOBOWITZ, H., "Electronic Computers" Doubleday & Co., Inc. 1963

4. D'AZZO, J., HOUPIS, C.H., "Feedback Control System Analysis and Synthesis" Mc Graw-Hill Book Co., Inc., 1966.

5. MOORE, A.W., "Phase-Locked Loops for Motor Speed Control" IEEE SPECTRUM April, 1973, P.61

6. OGATA, K., "Modern Control Engineering" Prentice-Hall, Inc., 1970

7. MILLMAN, J., TAUB, H., "Pulse, Digital and Switching Waveforms" Mc Graw-Hill, Inc., 1965

8. BOONYUBOL, C., "Transfer function of DC Motor" Experiment CS02., June, 1973

9. BESSANT, M.F., "MULTI-CHANNEL PROPORTIONAL REMOTE CONTROL" Wireless World, October 1973

APPENDIX A

EXPERIMENTAL MEASUREMENT OF MOTOR CONSTANTS

The moment of inertia and the friction of a motor and gear train system can be found by several exprimental means.[6,8]

Consider figure A1, The transfer function can be derived as [6,8]

$$\frac{\theta(S)}{E(S)} = \frac{K}{s\left[LaJs^2 + (Laf+RaJ)s+Raf + KKb \right]} \qquad (A1)$$

where

Ra	=	Armature-winding resistance, Ohms
La	=	Armature-winding inductance, Henrys
J	=	Equivalent moment of inertia of the motor and load referred to the motor shaft, slug - ft^2
f	=	Equivalent viscous-friction coefficient of the motor and load referred to the motor shaft, lb-ft/rad/sec.
K	=	Motor-torque constant
Kb	=	back emf constant

The inductance La is usually small and may be neglected, then transfer function reduces to

$$\frac{\theta(S)}{Ea(S)} = \frac{Km}{s(sTm + 1)} \qquad (A2)$$

where

$$Km = K/(Ra.f + K.Kb) = \text{motor gain constant}$$

$$Tm = Ra.J/(Ra.f + K.Kb) = \text{motor time constant}$$

Applying a step input of magnitude Ei, then from equation (A2), the resulting shaft velosity is

$$\theta(s) = \frac{Km.Ei}{s^2(sTm+1)} \qquad \text{(A3)}$$

Solving equation (A3), we have

$$\theta(t) = Km.Ei\ (t - Tm + Tm.e^{-t/Tm}) \qquad \text{(A4)}$$

The angular velocity $w(t)$:

$$w(t) = \frac{d}{d(t)}\theta(t) = Km.Ei(1 - e^{-t/Tm}) \qquad \text{(A5)}$$

At steady state, we have

$$w(\infty) = Km.Ei \qquad \text{(A6)}$$

Hence, Km can be found from equation (A6) by measuring the apply voltage and the motor speed. Tm can be found from equation (A5) by observing the transient speed of the motor system.

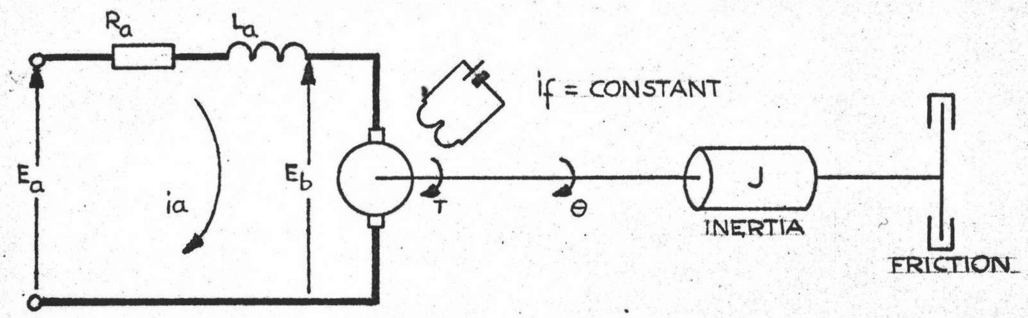


FIGURE A1. AN ARMATURE - CONTROLLED d-c MOTOR

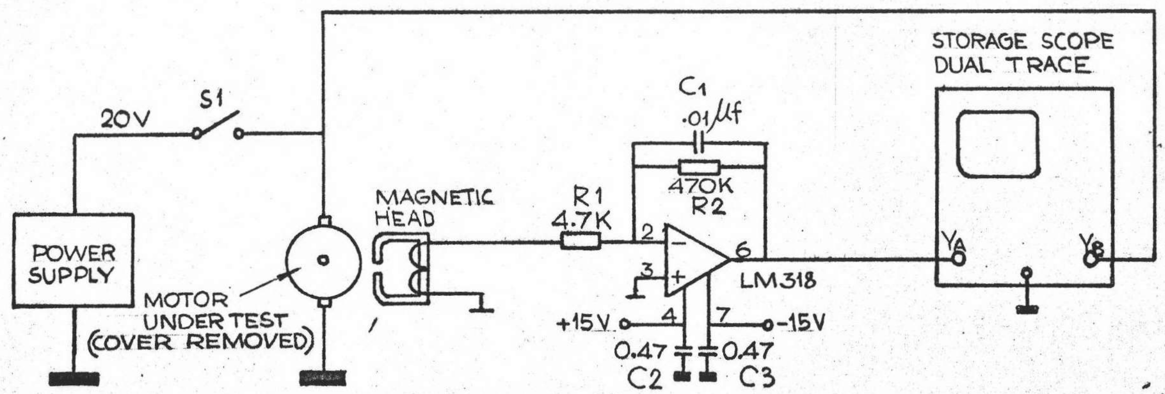


FIGURE A2. WIRING DIAGRAM FOR TESTING OF MOTOR CONSTANTS

The experiment was carried out by connecting up the equipments as shown in Figure A2, A magnetic head as used in a tape recorder was placed very near to the motor with the cover of the motor removed. As the motor rotates, a pulse train is generated, with a duration varies inversely as the motor speed. The waveform is filtered via an active filter network and recorded by a storage oscilloscope.

The test was started by closing switch s_1. The waveform was stored and taken by a Polaroid scope-camera as shown in Figure A3 and A4. Figure A3 shows the transient waveform recorded where the lower trace is the step input. Figure A4 shows the steady-state waveform

Since the motor used has five poles, therefore the motor will generate five pulses each revolution. From Figure A4:

$$\text{Steady-state speed} = \frac{1}{\text{average pluse duration}}$$

$$= \frac{1}{1.77 \times 5 \times 10^{-3}} \quad H_z$$

we have

$$w(\infty) = \frac{2}{1.77 \times 5 \times 10^{-3}} \quad \text{rad/sec}$$

$$= 710 \quad \text{rad/sec}$$

Using equation (A6), we have

$$Km = \frac{710}{20} = 35.5 \text{ rad/sec/volt} \qquad \text{(A7)}$$

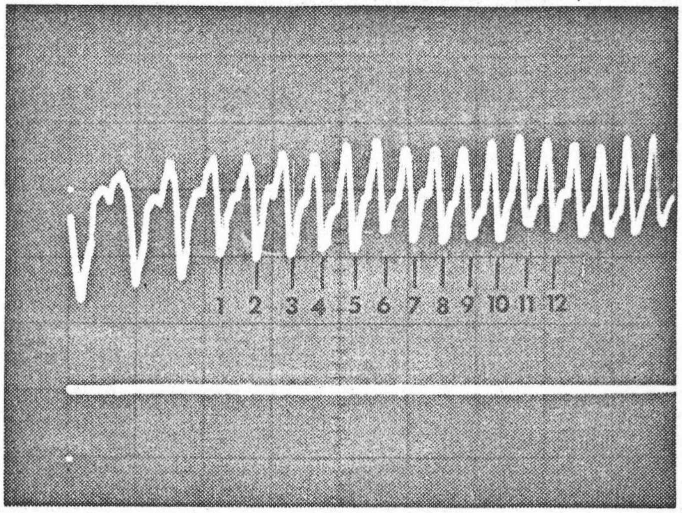


Figure A3. Upper trace: Response voltage from detecting coil when the motor is loaded, 1V/division.
Lower trace: Step input voltage applied to the motor, 20V/division.
Time bace : 5ms/division.

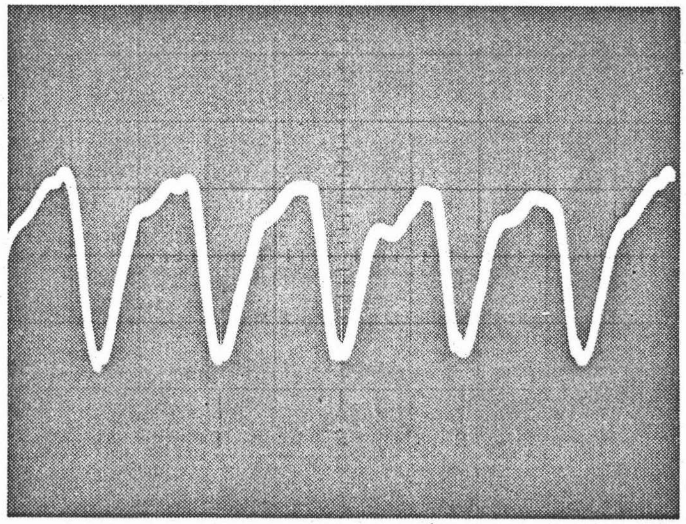


Figure A4. Steady-state voltage from detecting coil when the motor is loaded.
Trace scale : 2V/division.
Time base : 1ms/division.

From Figure A3, we select some definite intervals of the pulses and take the average time as the specific time for the interval selected. Appling equation (A5), we can calculate for T_m as tabulated below.

time interval (ms)	18.8-21.1	25.5-27.6,	31.7-33.7
average time (ms)	19.95	26.55	32.7
duration (ms)	2.3	2.1	2.0
motor speed (rad/sec)	546.39	598.16	628.32
T_m (sec)	0.0132	0.0145	0.0149

Hence $\quad T_m$ (average) $= 0.0142$ sec (A8)

APPENDIX B.

CONSTRUCTION

B.1 General

The controller built is to verify the design, therefore it may look bulky and not practical for use. The control system is separately built into two parts, a control unit and a remote unit. The dials of both units are used to indicate their angular position.

B.2 The Control Unit

The control unit consists mainly of two intergrated circuits, a potentiometer with dial and four dry-cell battery as self-contained power supply as shown in Figure B1 on the left. All are fixed on a plastic frame-work. The integrated circuits with their sockets and a few components are mounted on a small piece of universal board as shown in Fugure B2.

B. 3 The Remote Unit

An aluminum frame is used to house all the remote components and it may be mounted on a standard 19" rack and requires a 3-M space. as shown in Figure B1.

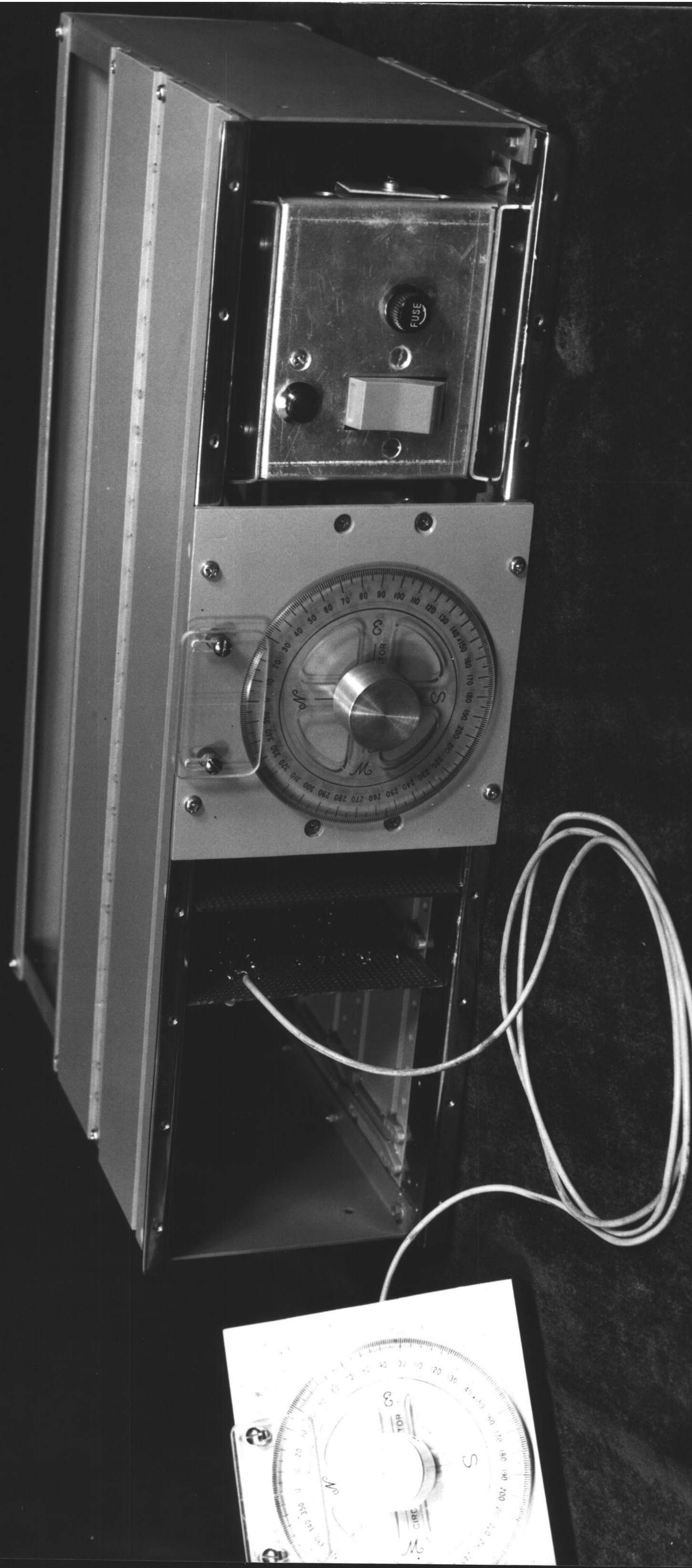
The frame accommodates two universal cards, a motor and gear-train unit, and a power supply unit.

The two cards are shown in Figure B3, one is for integrated circuits where the other is for amplifier section only. They are mounted in a plug-in manner, but they are wired directly at present stage which may put plugs and sockets on if required.

The motor and gear-train system shown in Figure B4 is mounted next to the cards with the dial faced out, and the feedback potentiometer is mounted at the rear and coupled to the same shaft as the dial.

B. 4 The Power Supply Unit

The power supply unit is shown in Figure B5, the circuit diagram is shown in Figure B6. Three outputs are provided, i.e. + 24V, - 24V and + 5V. Each output is regulated by a simple circuit and able to supply a maximum current of 500 mA. The + 24V and - 24V outputs enable us to design the amplifier in two configurations, i.e. the half-bridge which uses both + 24V and - 24V outputs, where the full-bridge circuit uses only the + 24V supply.


FUSE

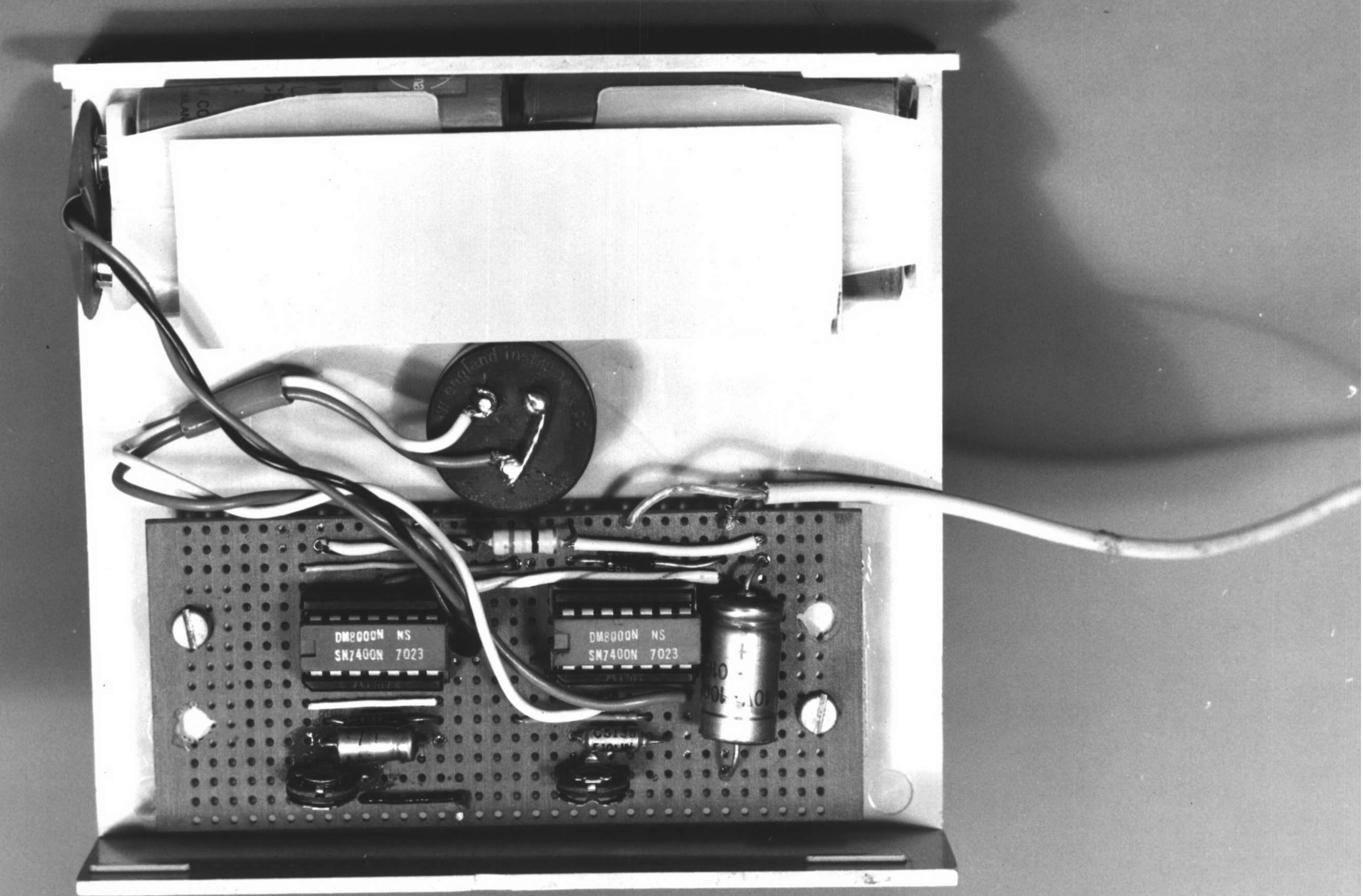
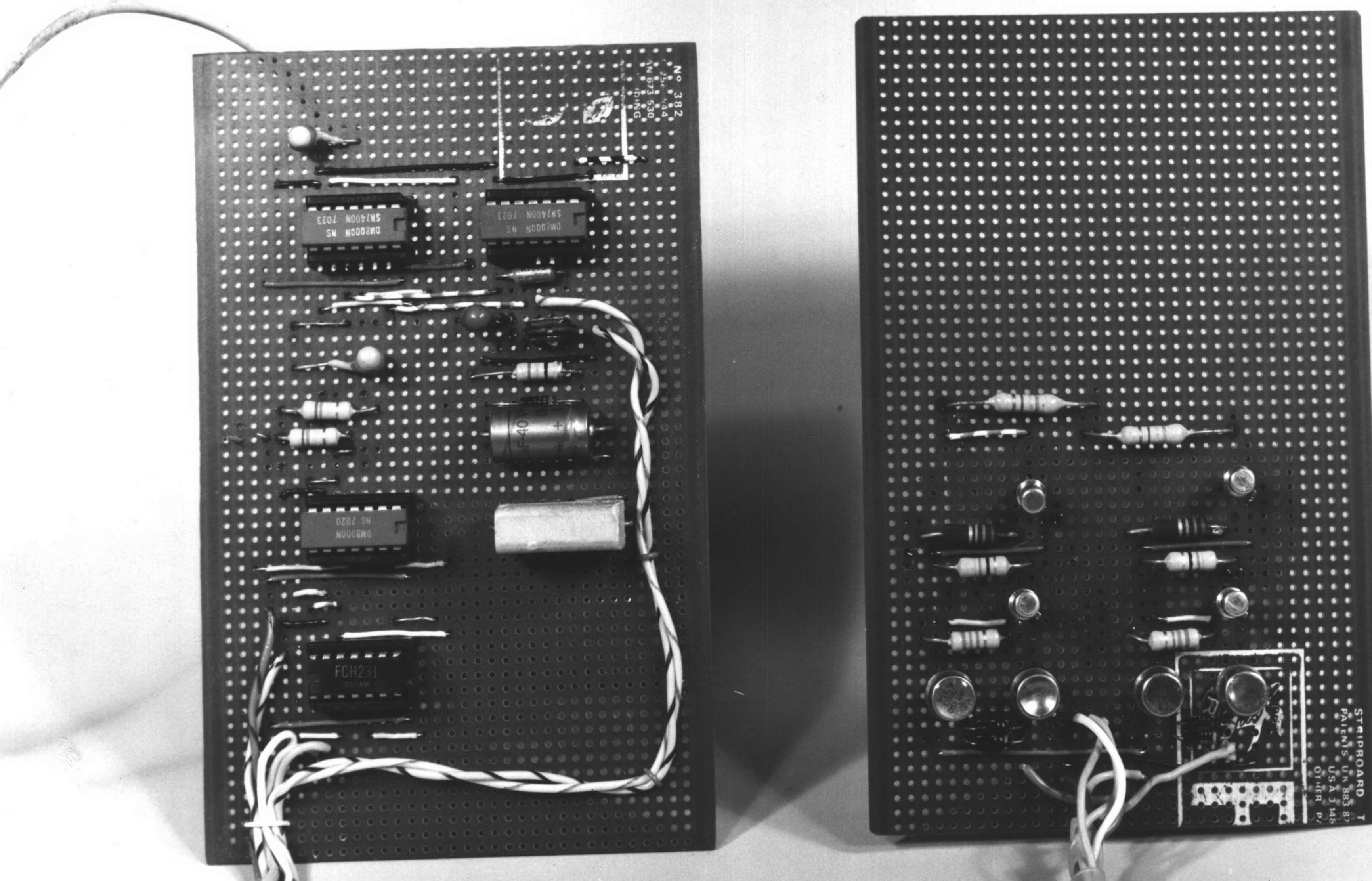


FIGURE B2. THE CONTROL UNIT, REAR VIEW.



(a) INTEGRATED CIRCUIT CARD

(b) AMPLIFIER CARD

FIGURE B3. ELECTRONIC CARDS

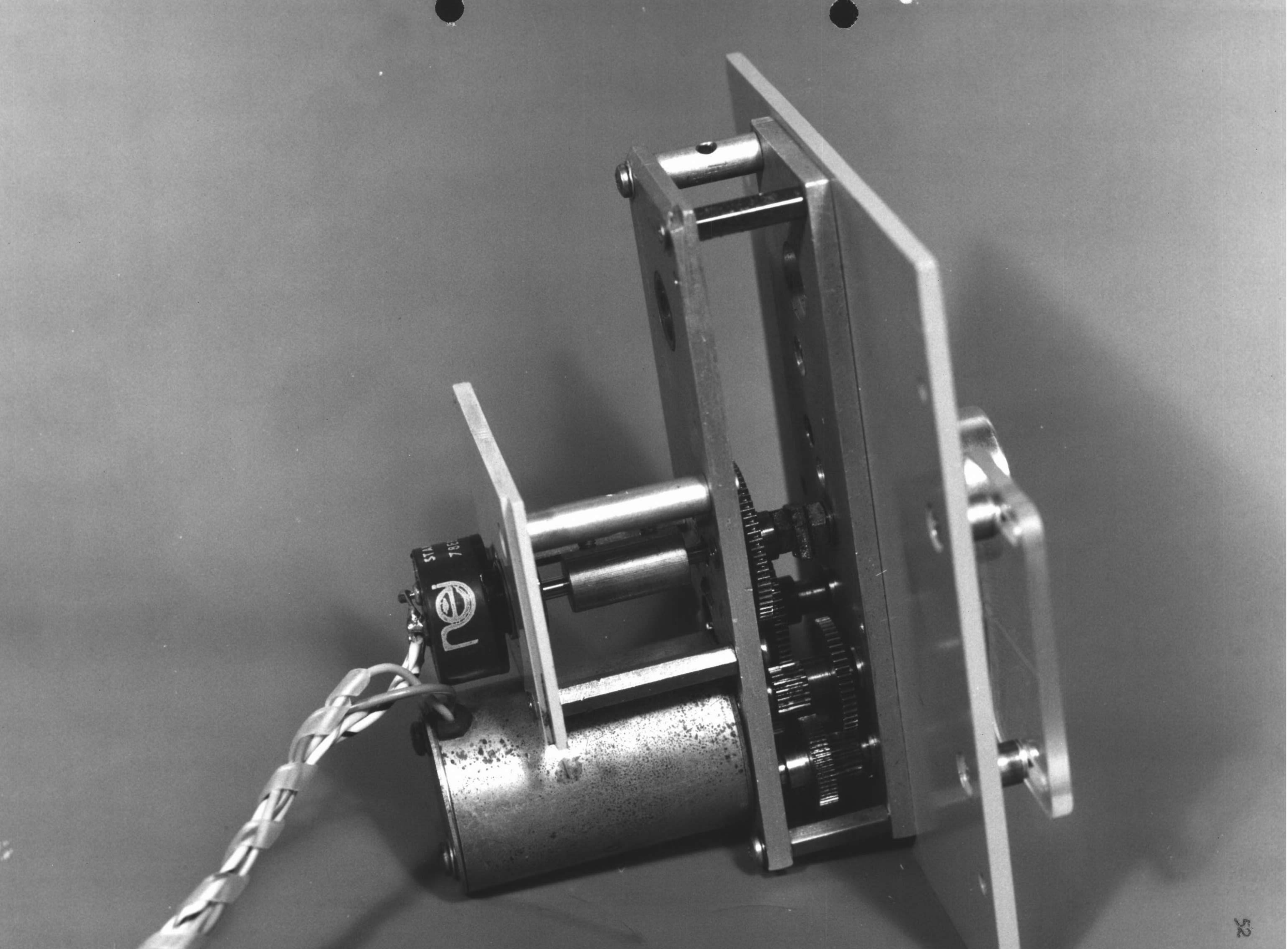


FIGURE D4. THE MOTOR AND GEAR TRAIN

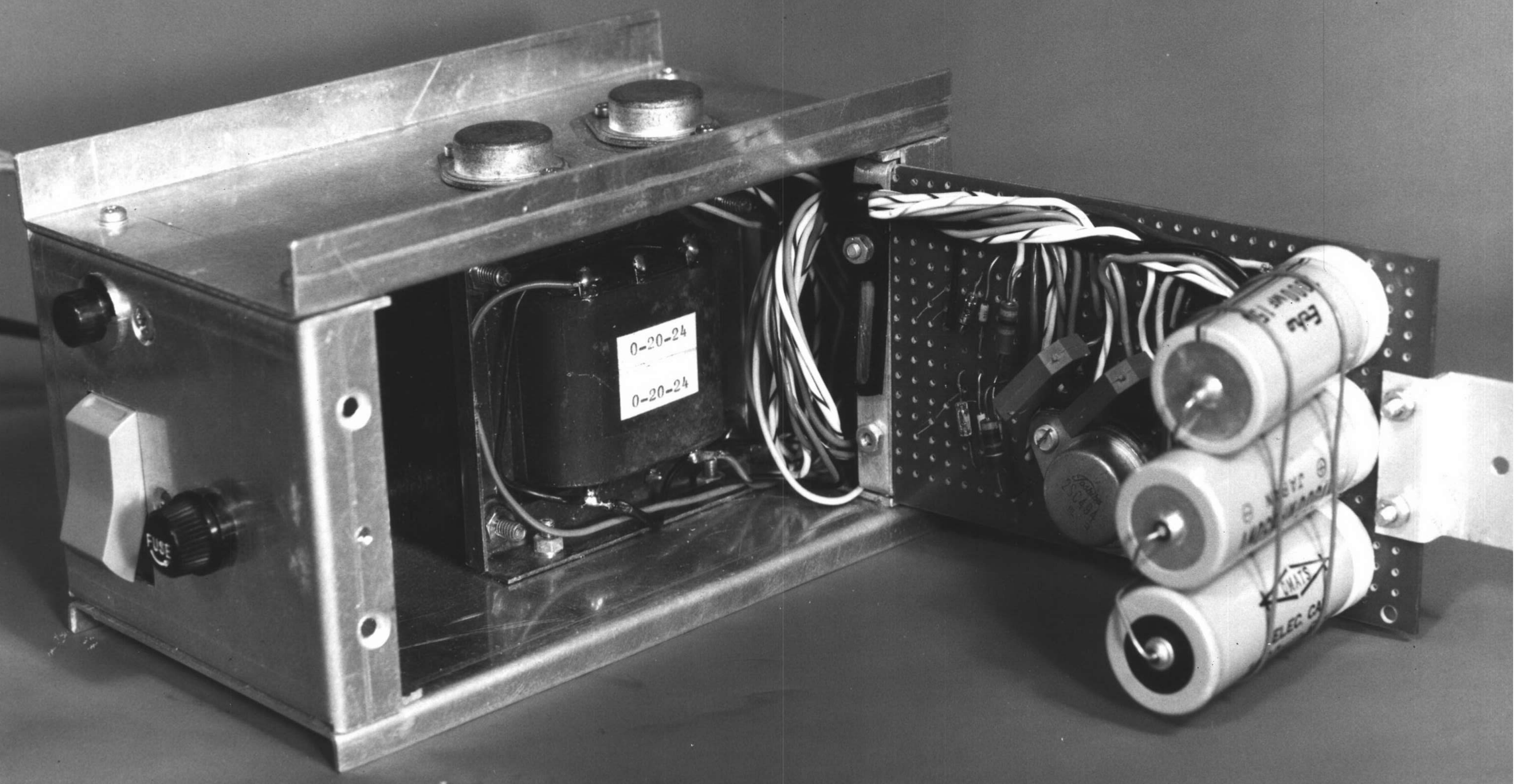


FIGURE B5. THE POWER SUPPLY UNIT.

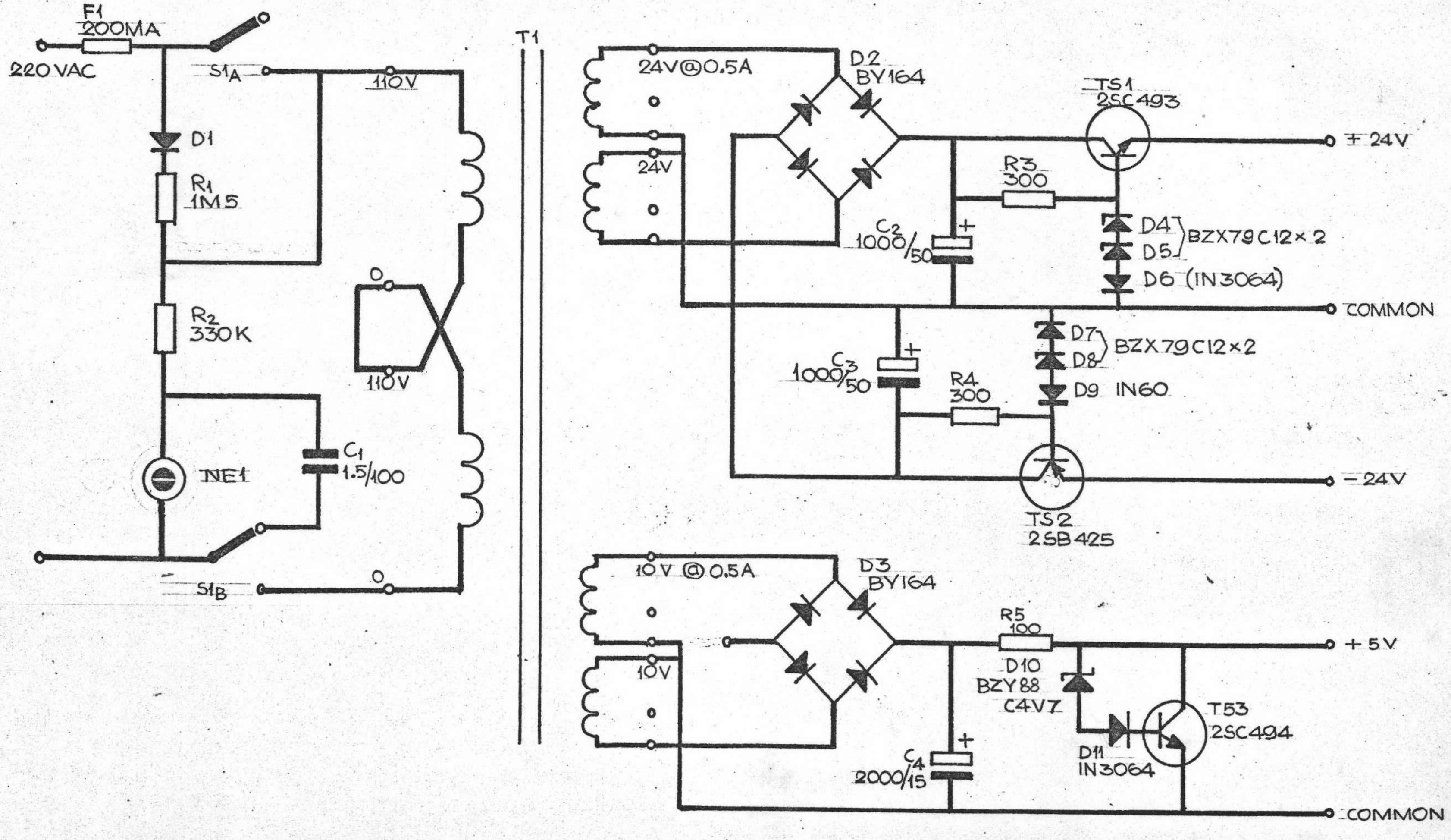


FIGURE B6. POWER SUPPLY CIRCIUT DIAGRAM

VITA

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