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Grossenbacher, Armen C., "The Design of an Automatic Electronic Preamodizer" (1976). *Dissertations and Theses*. Paper 4041.

<https://doi.org/10.15760/etd.5925>

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AN ABSTRACT OF THE THESIS OF Armen C. Grossenbacher for the Master of Science in Applied Science presented May 14, 1976.

Title: The Design of an Automatic Electronic Preatnodizer.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

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The topic of this thesis is the design of an automatic preanodizer to be used to preadjust precision tantalum resistors by anodizing their surfaces. The purpose of the preanodizer is to generate a controllable voltage ramp to be applied to a set of tantalum resistors which are immersed in a suitable electrolyte. The slope and maximum value of the voltage ramp are set to produce the current required for proper anodization of the resistors. The rate of anodization determines the rate of change of the resistor value. This thesis covers the design of an electronic device to meet a set of requirements specified by the Western Electric Company. The primary tasks the device has to perform are the generation of a linear voltage ramp of adjustable slope and maximum voltage and the supply of a given maximum

current. Metering circuits are provided to measure, store and display the current and the maximum value reached by the ramp voltage.

The device contains the logic circuits necessary to start the ramp on operator command. The logic also detects the amplitude of the ramp voltage and stops it when it reaches the value set on a maximum voltage control. The logic circuit lights an error light when the ramp does not complete a normal cycle.

The requirements of the device covered many areas in electronic technology. The author had to do considerable research in these different areas in order to design the necessary circuits. The areas of concern are as follows:

1. Power supply. Involved the study of the characteristics of modern power transformers, rectifier diodes, integrated circuit regulators and filter elements.
2. Power amplifier and preamplifier. Involved the study of power transistor circuits, methods of compounding multiple transistors to withstand the required power and provide sufficient gain, methods of driving the power amplifier and methods of dissipating the heat generated.
3. Ramp generator. Involved the study of function generation circuits and their control.
4. Metering circuits. Involved the study of sample and hold circuits and operational amplifier scaling circuits.
5. Logic circuits. Involved the study of various logic families and the decision making and switching methods that could be accomplished.

The design was completed and a production run of ten units was made. A calibration and test procedure was written in order to test the various circuits over a wide range of input voltages and ambient temperature. The tests were run on the production quantity of ten units. All ten units passed all requirements with a safety factor of 2 or more. The units have been in daily operation at the Western Electric plant for approximately two years. To this date none of the units have failed. The Western Electric Company is pleased and the designer is quite happy to have achieved this measure of success with his project.

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of
Armen C. Grossenbacher presented May 14, 1976.

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INTRODUCTION

The subject of this thesis is an electronic device called an automatic preanodizer ESI model SP 3699, which is an accessory to the ESI model SP 3477 anodizing system designed and produced by Electro Scientific Industries for the Western Electric Company. The system is used to adjust the value of tantalum resistors by precision anodization of their surfaces. The purpose of the preanodizer is to make a preliminary adjustment of the resistors. The preanodizer was assigned to A. C. Grossenbacher as an engineering design project. See Figure 3 for an outline drawing, and Figure 11, page 3, for a block diagram, of the unit. The preanodizer generates a controllable voltage ramp to be applied to a set of tantalum resistors which are immersed in a suitable electrolyte. The slope and maximum value of the voltage ramp are set to produce the current required for proper anodization. The rate of anodization determines the rate of change of the resistor value.

The design objectives were determined from requirements set by the Western Electric Company. Additional requirements were considered necessary for equipment safety and product protection. Among these added features are two levels of current limiting, voltage foldback at the current limit and an error mode providing indications of improper preanodization such as a short circuited load.

NOTE:

- A1 CROSS POINT SCANNER, 23018
- A2 PRE AMP, 27146
- A3 INTEGRATOR, 27103
- A4 LOGIC, 27101
- A5 METERING Ckt, 23067
- A6,7 METER SAMPLE & HOLD, 23069

Figure 3. Outline drawing of preanodizer

THE TANTALUM RESISTOR

The Western Electric Company collaborating closely with scientists of Bell Telephone Laboratories have developed a high volume manufacturing method for the production of precision tantalum thin film resistors and capacitors. Tantalum technology complements the silicon technology used for the production of transistors, diodes and now critical resistors on integrated circuits, Berry, Hall and Harris (1). These two technologies have made possible the mass production of integrated circuits, active filters and tuned amplifiers used in communication devices such as the touch-tone telephone.

I DESCRIPTION OF TANTALUM RESISTOR FABRICATION

The resistor is fabricated by depositing a thin film of tantalum or tantalum nitride on an insulating substrate such as ceramic. The deposition is made approximately 30% thicker than calculated so that all resistors will have a resistance lower than the desired value. An electrolytic paste is then applied to the resistor surface and dc current is passed through the electrolyte and the tantalum resistor as shown in Figure 1. This current converts the resistor's surface to an insulating oxide. This process is called anodization and it produces two desirable qualities:

1. The resistance value is increased because as the surface is being converted to an insulating oxide, the conduction path is made thinner. The increase in oxide formation (and resistance value) is closely related to the current density and the time the current is allowed to flow as shown in Figure 2. The value of the resistor can be precisely adjusted by carefully controlling these two parameters.
2. The surface is protected because the volume of oxide formed by the anodization process for both tantalum and tantalum nitride materials exceeds the volume of the original material involved in the conversion as shown in Figure 2. A layer of a tightly knit molecular structure is produced which serves as an excellent insulating protective coating on the resistor's surface.

Figure 1. Resistor being anodized

Figure 2. Growth rate versus current density

The typical resistors are 70 to 250 nanometers thick. The anodization process produces Ta_2O_5 at a rate of one oxide molecule for each ten electrons removed. Thus the rate of oxide formation is directly related to current density and time. The volume conversion rates for a one coulomb charge (one ampere-second) are 0.023 mm^3 of metal converted to 0.057 mm^3 of oxide for pure tantalum and 0.025 mm^3 of metal converted to 0.09 mm^3 of oxide for tantalum nitride.

II DESCRIPTION OF THE PRODUCTION EQUIPMENT

The design requirements for the anodization equipment were to measure and adjust these resistors to tolerances of 2% at a rate of four per second and to a tolerance of 0.01% at a rate of one per second.

These resistors are on a ceramic substrate approximately 4 cm by 8 cm. Each substrate has up to ten resistors and several capacitors which serve as tuning elements for frequency filters. Up to 20 of these substrates are connected at one time. An electrolyte is applied to the resistors through a suitable mask. The substrates are placed in a fixture with probes connecting each resistor to the measuring and adjusting system. At the start of the sequence up to 200 resistors are relay switched to the preanodizer (the subject of the thesis) which applies a voltage ramp, which is controllable in amplitude and time duration. This voltage ramp creates a constant current for a definite time period through all of the resistors to produce an initial anodized layer. This anodized layer brings all of the resistors to within measurement range of the main anodizing system. At the end of the preanodizing cycle the preanodizer automatically switches the entire batch of resistors to the main system where each resistor is relay switched to a resistance measuring system under computer control. The computer compares the measured value with the desired value stored in its memory and determines an anodizing current and time required to bring the resistance up to value. The computer sets these values into a time and amplitude controlled current source. The relays next switch the programmed current source to the resistor. The computer then sequences the measuring system to the next resistor. This process is continued through all of the resistors with an end of process signal indicating when all the resistors are within their tolerance limits.

REQUIREMENTS AND SPECIFICATIONS

The preanodizer was designed to meet the following requirements and specifications as set forth by the Western Electric Company. See Figure 11, page 3, for a block diagram.

1. Produce a voltage ramp that is variable in rate from 150 volts per minute to 2500 volts per minute with an accuracy of $\pm 5\%$.
2. Provide an adjustable maximum voltage limit such that the voltage reached by the ramp can be set from zero to -100 volts with an accuracy of $\pm 5\%$.
3. Provide sample and hold circuits to store the maximum load voltage and current reached during the preanodizing cycle and feed these values to front panel meters for display with an accuracy of $\pm 3\%$.
4. Provide a current limiting circuit such that the maximum current during a normal preanodizing cycle will be 2 amperes but will drop to 1 ampere maximum in case of a load resistance which is so low that the voltage cannot be followed at a load current of 2 amperes. This requirement allows a tantalum resistor, or group of them, which starts with a very low surface resistance, to be anodized with a lower current level. As the anodized layer builds, the surface resistance increases and the current limiting circuits can return to normal.
5. Provide relay switching so that the resistors being anodized are switched to the preanodizer during its cycle, then switched back to the multiplexer of the ESI model SP 3477.
6. Provide a circuit that will detect when the preanodizing cycle was not successfully completed, i.e., the maximum ramp voltage was never reached due to a load resistance too low to support the ramp voltage at the current limit values. This circuit monitors the output voltage ramp and allows a time of 20% longer than normal for the ramp to reach V maximum. If the ramp fails to reach V maximum the circuit

lights an error lamp indicating a dV/dt error and stops the cycle without transferring the leads to the ESI model SP 3477. This allows the operator to determine the cause of error by noting the values of voltage and current held by the meters, and to take appropriate action.

7. Provide a front panel control that will switch the preanodizer into or out of the process. When switched out the meters on the preanodizer must be returned to zero and the dV/dt error light must be extinguished if lit.

The above requirements were all met and in most cases exceeded by the device described in this thesis.

DESIGN OF NECESSARY CIRCUITS

The circuits necessary to perform the preanodizing function are discussed in the following subsections.

Subsection I, POWER SUPPLY, discusses the power supply that converts the line voltage of 117 volts rms to the dc voltages required by the power amplifier.

Subsection II, POWER AMPLIFIER, discusses the power amplifier that controls the current and voltage applied to the load.

Subsection III, PREAMPLIFIER AND CURRENT CLAMP, discusses the preamplifier necessary to provide the amplification required between the ramp generator and the power amplifier.

Subsection IV, INTEGRATOR (RAMP GENERATOR), discusses the integrator which generates the ramp voltage of a preset amplitude and slope.

Subsection V, CURRENT AND VOLTAGE METERING CIRCUITS, discusses the current and voltage metering circuits.

Subsection VI, CONTROL LOGIC, discusses the logic required to control the various sections of the preanodizer.

I POWER SUPPLY

See Figure 11, page 3. The regulated ± 15 volts required by the operational amplifiers and the regulated 5 volts required by the logic are obtained externally. The power supply in the preanodizer needs to supply only the power requirements of the load through the power amplifier.

The requirements on the power supply are that it be able to deliver a maximum current of 2 amperes to the load at a maximum voltage of 100 volts dc.

Power Transformer Selection

The rms output voltage of the power transformer is calculated on the basis of insuring 100 volts dc across the load at maximum load current with low line voltage, considering the output transistor drop and the percent load regulation

allowed by the filter capacitor. Assume the following conditions:

1. The dc output of a capacitor filtered power supply is $\sqrt{2}$ times the rms voltage applied.
2. Low line voltage = 100 V.
3. The total voltage drop across the four series-connected output transistors is 4 times the individual saturation voltage of each one with 2 amperes flowing. Figure 8 is the curve of saturation voltage versus collector current for the 2N6259 transistor. It shows a saturation voltage less than 0.2 volt at 2 amperes. For this analysis we will conservatively use 0.5 volt per transistor giving 2 volts total for the four in series.
4. The transformer resistance is less than 5 ohms.
5. The output stage has been designed as an emitter follower so that any reasonable variation in collector voltage will not be present across the load. This can be verified by looking at Figure 7 of the 2N6259 transistor curves and noting that the change in collector current versus collector voltage around 2 amperes is approximately 10%. The load regulation allowed by the filter capacitor can then be set at 10%. This would yield a change in load current versus filter characteristics of 10% of 10% or 1% which is well within the design requirements.

The transformer output voltage can now be calculated, Boylestad and Washelsky (2), as:

$$V_L = \sqrt{2} V_T (1 - E_T) - V_Q - I_L R_T - V_R$$

$$V_T = 89.19V$$

where

$$V_L \quad \sim \text{Load voltage } 100V \text{ dc}$$

$$V_T \quad \sim \text{Transformer open-circuit output voltage in volts rms}$$

$$E_T \quad \sim \text{Transformer loss } 0.1 \text{ proportional parts (10\%)}$$

$$V_Q \quad \sim \text{Transistor voltage drop } 2V \text{ dc}$$

$$I_L \quad \sim \text{Full load current } 2A \text{ dc}$$

Figure 7. Typical output characteristics for type 2N6259

Figure 8. Typical saturation-voltage characteristics for type 2N6259

R_T - Transformer winding resistance 5Ω

V_R - Rectifier voltage drop 1.5V dc

The transformer can then be a one to one ratio which will yield 89.2 volts at a low line voltage of 100 volts at 89.2% transformer efficiency. The unit selected to meet the requirements is a Stancor model P 6415 which has the following specifications:

1. A transformer ratio of 1.07 to 1 giving 107 volts out with 100 volts in. This would yield 89.12 volts out with 100 volts in at 83% efficiency.
2. Secondary resistance of 3.15 ohms.
3. Current output of 3 amperes at 117 volts and 350 watts.

Diode Bridge Rectifier (CR5) Requirements

The diode bridge rectifier must provide 2 amperes continuous current with a maximum dc voltage drop of less than 1.5 volts and must be able to withstand a reverse voltage of $\sqrt{2}$ times the rms value of the highest line voltage encountered. Assuming 130 volts to be a maximum line voltage, the inverse voltage would be:

$$V \text{ inverse} = 1.414 \times 130V = 183.82V \text{ dc}$$

The rectifier selected was the Motorola MDA 952-4 silicon bridge rectifier which has 6 amperes continuous forward current, 1.3 volts forward drop at 2 amperes and a reverse voltage rating of 400 volts.

Filter Capacitor Requirements

The filter capacitor must provide a voltage change of less than 10% at the rated current drain of 2 amperes. The capacitor must provide the 2 amperes to the load during the periods between diode conduction which is approximately 8 milliseconds for a full wave rectifier producing pulsating dc at a frequency of 120 Hz. The capacitor value is calculated, Radio Corporation of America (3), as follows:

$$I_C = C \frac{dV}{dt} K$$

where

I_C - Load current supplied 2A dc

C - Capacitor capacitance in farads

dV/dt - Time rate of change of voltage $(1/8) \times 10^5$ V/s

K - Permitted voltage drop 0.1V/V

therefore

$$C = 1600 \mu F$$

A bleeder resistance of 13 kilohms was connected across the filter capacitor. This allows the power supply to discharge to approximately 37 volts in 20 seconds (one RC time of $(13)(10^3)(1600)(10^{-6}) = 20$ seconds). This is fast enough to allow protection to a service person gaining entry to the unit.

II POWER AMPLIFIER

Refer to Figure 12, power amplifier and Figure 13, page 15, preamplifier.

Several types of power amplifier circuits were considered before the final design was chosen.

Two general types of circuits presented in the literature, Radio Corporation of America (3) and Cutler (5), were finally singled out for final consideration. One type is a common-emitter connection which provides the output from the collectors of the output transistors. This type of circuit provides an excellent isolation of the load from the power amplifier because of its high collector impedances and would be thus an excellent choice for a current output application. The pre-anodizer, however, requires that the output be a linear voltage ramp rather than a current ramp. This voltage ramp could have been achieved with suitable negative feedback from the load to the preamplifier input. This method was tried but rejected because the load could consist of not only fairly low resistance but of a fairly high capacitance. When this capacitance was simulated the phase of the feedback back loop shifted far enough for the circuit to oscillate.

The other type of power amplifier circuit, which was the choice for this project, is called an emitter follower. The load is placed in the emitter circuit and the collector is held at signal common. The output voltage across the load now follows the variation of input voltage applied to the bases within one emitter base diode voltage drop. All negative feedback required for stability and signal linearity can now be done in the preamplifier which provides isolation from the capacitance and assures stability.

Figure 12. Power amplifier assembly

Figure 13. Preamplifier circuit assembly

Selection of Power Transistors

The power that must be dissipated in the power/amplifier transistors is maximum at the start of the ramp. At this point there could be as much as two amperes of current flowing with all the power supply voltage dropped across the power transistors. If we assume a maximum line voltage of 135 volts, the maximum power the transistors would dissipate is:

$$P = V N I \sqrt{2}$$

$$P = 408 \text{ watts}$$

where

P - Maximum transistor power dissipation in watts

V - Maximum line voltage 135V rms

N - Transformer turns ratio 1.07

I - Maximum current 2 A dc

A single transistor capable of dissipating 408 watts would be much too expensive. Multiple transistor circuits which would distribute the power dissipation among several transistors were studied. Connecting transistors in parallel to reduce the current flow through each transistor was not practical in this design because of the high voltages (204 volts) involved. The method chosen was to use four transistors in series to reduce the voltage drop across each to approximately 51 volts maximum. At 2 amperes this is a power dissipation requirement of 102 watts maximum per transistor. The transistor selected was the RCA 2N6259 which is capable of 250 watts dissipation if the case is kept at 25°C as seen in Figure 4.

Selection of Heat Sinking Methods

Since it is impractical to remove all the heat from the device so that its temperature would remain at 25°C, we must determine what temperature can be allowed. The transistor junction temperature cannot go above 200°C, Figure 5, page 18, without damage at the required power dissipation of 102 watts maximum.

The heat sinking requirements are determined by use of the thermal analogy to Ohm's Law shown in Figures 9 and 10, page 19. From this analogy we see that the junction temperature is:

Figure 4. Maximum operating areas for type 2N6259

Figure 5. Thermal-cycle rating chart for type 2N6259

Figure 6. Typical dc beta characteristics for type 2N6259

Figure 9. Thermal analogy to Ohm's Law

Figure 10. Junction to ambient temperature distribution of transistor

$$T_j = T_a + P(\theta_{jc} + \theta_{cs} + \theta_{sa})$$

where

P - Power dissipated in watts

θ_{jc} - Thermal resistance of junction to case

θ_{cs} - Thermal resistance case to sink

θ_{sa} - Thermal resistance of sink to ambient

The thermal resistance (θ_{jc}) for a 2N6259 transistor is 0.7°C per watt. Using mica insulators and heat sink grease to mount the transistor to the heat sink yields a case to sink thermal resistance (θ_{cs}) of approximately 0.5°C per watt. The ambient temperature of the area the preanodizer is to operate in would not exceed 30°C . The heat sink thermal resistance is calculated as follows:

$$\begin{aligned}\theta_{sa} &= \frac{T_j - T_a}{P_{\max}} - \theta_{jc} - \theta_{cs} \\ &= \frac{(200^\circ - 30^\circ)\text{C}}{102 \text{ watts}} - (0.7 + 0.5)^\circ\text{C per watt} \\ &= 0.5^\circ\text{C per watt}\end{aligned}$$

The heat sink chosen was a Wakefield model NC413 for each transistor. These were mounted in a sheet metal tunnel with a Rotron model 174 fan blowing air at 100 cubic feet per minute through the tunnel over the sinks as seen in Figure 12, page 14. This combination provides a θ_{sa} of less than 0.25°C per watt which provides a two times safety factor over the requirement.

Power Amplifier Circuit

The input base drive current required for a 2N6259 is determined from the curves of H_{fe} shown in Figure 6, page 18. From Figure 6 the current transfer ratio for an output current of 2 amperes is 80. In this design an H_{fe} of 50 was assumed to be conservative. The input base drive current required is then:

$$I_{\text{base}} = \frac{I_{\text{collector}}}{H_{fe}} = \frac{2 \text{ amperes}}{50} = 40 \text{ ma}$$

In order to reduce the current drive requirements of the preamplifier it was decided to provide the base current for each power transistor from a separate 2N4920 transistor, as shown in Figure 12, page 14, and Figure 13, page 15. This method of direct couple driving is called a compound feedback pair, Cowles (4), of which there are several choices. This compound pair was chosen over the usual Darlington connection because it has only one diode voltage drop between the input base circuit and the load in the emitter follower circuit yet still provides the product of the individual transistor current gains as a total circuit current gain. The minimum H_{fe} for the driver transistor, 2N4920, for 40 milliamperes of collector current is 40. The input drive current for each compound pair for 2 amperes output is then 1 milliampere. The 2N4920 driver transistors are also mounted in the fan cooled tunnel to insure proper power dissipation. Resistors R1, R4, R11 and R14 between the bases equalize the voltage drop across each compound output pair. Their values must be chosen low enough to not cause excessive voltage drop due to base currents, yet must be high enough to not require too much drive current from the preamplifier. The values chosen were 1 kilohm which will drop only 1 volt for each 1 milliampere of base current. The preamplifier current requirement is maximum when all the power supply voltage is dropped across the four 1 kilohm base drive resistors and none is across the output load. At the highest expected dc voltage of 180 volts the maximum current required by the four 1 kilohm resistors is then 45 milliamperes which can be supplied easily by the driver transistor mounted on the preamplifier board. The power rating required for each 1 kilohm resistor at 45 milliamperes is 2.025 watts which was met by using 2 watt resistors placed in the cooling tunnel. The other components used in the power amplifier circuit and their purposes are as follows:

1. Diodes CR1, CR3, CR11 and CR13 provide protection to the 2N4920 base-emitter junctions against reverse voltage spikes.
2. Diodes CR2, CR4, CR12 and CR14 are 75 volt zener diodes insuring that none of the four compound paired output stages can be destroyed by over voltage.
3. Resistors R2, R5, R12 and R15 are necessary to provide low resistance paths to absorb collector to base leakage currents of the output transistors when they are turned off.

4. Capacitors C1, C2, C11 and C12 provide high frequency gain roll-off at a rate of 20 decibels per decade past 400 Hz which is the frequency at which the capacitive reactance reaches 100 ohms. This roll-off frequency is chosen to be approximately 10 times the maximum ramp rate of 2500 volts per minute (approximately 40 volts per second). A Fourier analysis of a sawtooth wave form shows that it is made up of the fundamental and higher harmonics of diminishing amplitudes. A frequency response 10 times higher than the signal fundamental frequency will pass up to the ninth harmonic which is enough to insure a ramp purity adequate to meet requirements. Roll-off of frequencies above those required eliminates higher frequency noise components and tendencies toward high frequency oscillation common to compound feedback pairs.

III PREAMPLIFIER AND CURRENT CLAMP

Preamplifier

The requirements of the preamplifier, Figure 13, page 15, are as follows:

1. Be able to work between ground and a minus 180 volt power supply.
2. Have a gain of 10 to provide a minus 100 volt output ramp with an input ramp limited to 10 volts by the 15 volt power supplies of the operational amplifier used in the ramp generator.
3. Supply sufficient output power to drive the 4 kilohm load of the power amplifier input over the required 100 volt ramp range.
4. Provide two levels of current clamping.

Commercial operational amplifiers that could meet the preamplifier requirements were quite expensive. It was therefore decided to design a preamplifier using discrete components. The following description shows that the operation is very similar to a commercial operational amplifier.

1. The input transistor Q1 is connected as an emitter follower with R2 as a load resistor to the minus supply voltage which is connected to pins 10 and 11.

2. Resistor R2 is also connected to the base of Q2 which compounded with Q3 forms a common emitter amplifier with the power amplifier base resistors as a collector load.
3. The base of Q1 input is held very near to ground (point R14) by the fact that its emitter is held to approximately -0.6 volts by the base-emitter diode of Q2. A positive going voltage applied to point C will then develop a current through R1 that will appear to be sunk to ground.
4. The current variations required by the output load voltage variation are calculated as follows:

$$\Delta I_{eQ3} = (1 + H_{feQ3})(\Delta I_{bQ3})$$

but

$$\Delta I_{bQ3} = \Delta I_{cQ2} = (H_{feQ2})(\Delta I_{bQ2})$$

and

$$\Delta I_{bQ2} = \Delta I_{cQ1} = (H_{feQ1})(\Delta I_{bQ1})$$

and

$$(1 + H_{feQ3}) \approx H_{feQ3}$$

so the output current

$$\Delta I_{eQ3} = (H_{feQ1})(H_{feQ2})(H_{feQ3})(\Delta I_{bQ1})$$

where the small signal currents of the transistors are:

ΔI_{bQ1} - Base current of Q1 in amperes

ΔI_{bQ2} - Base current of Q2 in amperes

ΔI_{cQ2} - Collector current of Q2 in amperes

ΔI_{bQ3} - Base current of Q3 in amperes

ΔI_{eQ3} - Emitter current of Q3 in amperes

and the small signal current gains are:

H_{feQ1} - Current gain of Q1 in proportional parts

H_{feQ2} - Current gain of Q2 in proportional parts

H_{feQ3} - Current gain of Q3 in proportional parts

H_{fe} is the small signal current gain of the transistor. The H_{fe} 's of the transistors used are all above 100 so the quantity $(1 + H_{fe})$ can be simplified to H_{fe} with less than 1% error.

The minimum H_{fe} of the 2N3053, 2N5416 and 2N3439 are all above 100 yielding a total preamplifier current gain in excess of 10^5 . With this high current gain it is obvious that all but one part in a million of the current in R1 will flow through R3. The voltage gain can then be calculated:

we have

$$I = I_{R1} = I_{R3} = \frac{V_I - V_G}{R1} = \frac{V_G - V_O}{R3}$$

for

$$V_G = 0$$

this gives

$$\frac{V_O}{V_I} = \frac{R3}{R1}$$

where

I - Input current in amperes

I_{R1} - Current through R1 in amperes

I_{R3} - Current through R3 in amperes

$R1$ - Input resistance in ohms

$R3$ - Feedback resistance in ohms

V_I - Input voltage in volts

V_O - Output voltage in volts

V_G - Signal-ground voltage (reference)

Transistors 2N3439 and 2N5416 were chosen to sustain the 180 volts maximum required by the preanodizer.

The power dissipation of the output transistor Q3 is maximum when its output impedance is equal to the 4 kilohm load it must drive. This occurs during the amp when one half of the 180 volts is dropped across the 4 kilohm collector load and one half is dropped across the transistor. This power is calculated as:

$$(90V)^2/4k\Omega \approx 2W$$

This power dissipation is met with natural convection by a Wakefield NF 205 heat sink on the TO-5 case of Q3.

Diodes CR1 and CR2 are for reverse base to emitter protection of Q1 and Q2.

C1 provides stability by reducing the gain of Q1 at high frequencies.

Current Clamping Circuit

Two Amp Clamp Circuit. The load current must pass through the 0.9 ohms provided by resistors R7, R8, and R9 connected in parallel. When the load current reaches 2 amperes it develops 1.8 volts across the series connection of diodes CR4, CR5 and the base-emitter diode of Q5 providing 0.6 volts each causing them to turn on. When they turn on they provide a current flow through resistors R1, R4, R11 and R14 producing a voltage of the proper polarity to decrease the conduction of the output transistors thus clamping the output current at 2 amperes. R7, R8 and R9 are precision wire wound resistors to provide stability of current clamp level.

One Amp Clamp Circuit. If the load is low enough in impedance the 2 ampere current flowing through it cannot develop a voltage high enough to follow the output of the preamplifier. In this case the voltage at point W will be clamped to the following voltage:

$$V_W = V_{be_{Q1}} + V_R + V_{CR6} + V_L$$

where

$$V_W = \text{Potential at point W in volts}$$

- V_{beQ1} - Base-emitter drop of Q1 in volts
- V_R - Voltage across the parallel combination of R7, R8 and R9 in volts, with 2 amperes current flow, $V_R = 1.8V$
- V_{CR6} - Diode voltage drop of CR6 in volts, $V_{CR6} = 0.6V$
- V_L - Voltage drop of load impedance with 2 amperes current flow, in volts

As the output of the preamplifier at point E continues to rise, a voltage difference is produced across R6. This voltage in addition to the voltage drops of CR4 and CR5 and the emitter to collector voltage of Q5 (which is conducting because of the 2 ampere current clamping action) is applied to a voltage divider consisting of R4 and R5. When the voltage difference across R4 and R5 reaches approximately 8 volts, R4 will have 8/13 or 0.6 volts which will turn on transistor Q4. When Q4 turns on sufficiently its collector to emitter voltage will drop to approximately 0.3 volts. At this point, diodes CR4 and CR5 cannot conduct and the voltage across R7, R8 and R9 decreases to this 0.3 volts plus the 0.6 volt drop of the base-emitter of Q5. This provides a current of the following value:

$$I_R = 0.9V/R = 0.9V/0.9\Omega = 1A$$

where

- I_R - Current through resistance R
- R - Resistance of resistors R7, R8 and R9 connected in parallel

This one ampere current limit will continue as long as the output load voltage cannot follow the preamplifier output voltage due to a low load impedance.

Diode CR6 allows the power amplifier voltage output to be reduced to zero very rapidly at the end of the ramp cycle even though there might be a voltage stored in the load. This stored voltage is sensed and the load will not be allowed to switch to the main measuring system until this voltage has decayed to a safe value. This action is described further in Subsection VI. Precision resistor R12 produces a voltage proportional to the load current and supplies it to the current measuring circuits.

Precision resistors R10 and R11 divide the load voltage by 25 to be used by the voltage sensing circuits.

IV INTEGRATOR (RAMP GENERATOR)

The voltage ramp used to satisfy requirements 1 and 2 is produced by an integrator circuit, Figure 14, formed by operational amplifier U2 with the input resistor R12 and the feedback capacitor C1 forming the integration time constant. The rate of voltage change at the output of U2 is 1/10 of the final rate because of a gain of 10 in the preamplifier. The voltage ramp rate is a linear function of the current through C1, Burr-Brown Research Corporation (6). Since almost no current flows into the input of an operational amplifier, essentially all the current through C1 also flows through R12. If we assume the voltage at pin 3 of U2 to be very close to ground and the voltage at pin 2 to be equal to that at pin 3 because of the high gain of operational amplifier U2 then the current through R12 is determined by the voltage applied to it from the output of U1. The output voltage of operational amplifier U1 is equal to the voltage applied to the input resistor R6 times the ratio of the feedback resistor, R_F , (a variable rheostat labeled dV/dt SET) and R6. These relationships are as follows:

$$dV/dt = It/C1$$

$$I = kR_F/R6$$

where

dV/dt - Voltage ramp rate in volts per second

I - Current into capacitor C1 in amperes

$C1$ - Capacitance of capacitor C1 in farads

t - Time in seconds

$R6$ - Input resistance to U1 in ohms

R_F - Feedback resistance (dV/dt SET) in ohms

k - Current constant in amperes

R6 is selected in value to achieve the required 250 volts per minute.

When the value of V maximum is reached as determined by a comparator on the logic board a positive 15 volts is applied to point 4 which turns on transistor Q1 which shorts out C1 and terminates the ramp. Resistor R13 limits the discharge current of C1 through Q1 to a safe value.

The output of U2 between ramps is adjusted to be a slight positive voltage that will bias the power amplifier very close to its turn on point. The voltage adjustment is necessary to compensate for the offset voltages of the integrator, pre-amplifier and power amplifier. The adjustment is made by providing a diode clamped -0.6 volts at the output of U1 and inserting a positive voltage variable from 0 to +1.0 volts to pin 3 of U1 and U2. This allows sufficient variation to compensate for the voltage offsets.

The voltage ramp output of U2 is fed to operational amplifier U3 where it is given a gain of approximately 0.3 by the ratio of R2 to R1. The output of U3 is fed to U4 which acts as a comparator against the V maximum set voltage fed in at pin 11. A positive logic level is put out on pin 17 when the voltage out of U3 exceeds the comparator set level. Diode CR7 and resistor R3 provide hysteresis for negative outputs insuring a positive trip level of U4. This circuit shuts down the logic and terminates the ramp in a time approximately 30% longer than the set ramp time in case of a short circuited load. This circuit also causes the dV/dt error light to go on, indicating that the load voltage did not build up to its set values, thus satisfying requirement 6.

V CURRENT AND VOLTAGE METERING CIRCUITS

Various meter scaling and sample and hold circuits were studied, Burr-Brown Research Corporation (6), Analog Devices (7), from which the following metering method was selected.

Current Metering

A voltage proportional to the current through the load is taken across R12 of the preamplifier, Figure 13, page 15, (0.1Ω) which is in series with the load. The voltage is applied to the signal amplifier on the metering board, Figure 15, where it is given a gain of approximately 3 because of the ratio of the 31.6 kilohm feedback resistor to the 10 kilohm input resistor. The signal is then passed to the sample and hold board, Figure 16, page 31, where it is given a gain of 10 by the ratio of the 50 kilohm feedback resistor to the 5 kilohm input resistor of M3. The M3 output voltage is applied to the storage capacitor C3. At the end of the ramp cycle relay K1 opens before the current in the load changes. With the input

Figure 15. Metering amplifier PCB assembly

resistor of operational amplifier M3 disconnected the only discharge of the voltage on C3 is due to the bias current of M3. A Burr-Brown 3112/12C was chosen for M3 for its very low bias current of 20 picoamperes at 25°C. The voltage decay across the 0.01 microfarad capacitor C3 can now be calculated as:

$$\frac{dV}{dt} = \frac{I}{C3} = \frac{(20)(10^{-12})}{(0.01)(10^{-6})} = \frac{2 \text{ millivolts}}{\text{second}} = \frac{0.120V}{\text{min}}$$

The panel meter used to indicate the current level has a resistance of 2 kilohms and requires 0.2 volts to drive it full scale. A full scale output voltage from M3 of only 0.2 volts would not be high enough to provide a stable meter reading when the storage capacitor is decaying at a rate of 0.12 volts per minute. To improve this situation the meter resistance was shunted to 68 ohms and is supplied from M3 through approximately 3 kilohms. This provides an approximate 70 to 3000 voltage division allowing the output of M3 to be

$$(0.2V) \frac{(3070)}{70} \approx 8.77 \text{ volts}$$

The meter reading will then decay at a rate of approximately

$$\frac{0.12}{8.77} \times 100 = 1.4\% \text{ per minute}$$

which is sufficient to maintain accurately held meter readings between ramp cycles. Relay K1 is turned on during the ramp cycle by the logic board which applies a positive logic level to transistor Q2. The current through Q2 flows through the bases of Q1 and Q3 turning them on. Transistor Q3 supplies turn on current for the relay coil of K1. Transistor Q1 supplies current to the in-process light on the panel indicating that a ramp cycle is in process. The current meter reads 3 amperes full scale. This 3 amperes is converted to 0.2 volts across the meter as follows:

$$V_M = R_S I G_M G_S G_D = 0.21V$$

where

V_M - Meter reading in volts (proportional to current)

R_S - Resistance of shunt in ohms (0.1Ω)

I - Full scale current in amperes (3A)

G_M - Metering board gain in proportional parts (3.16)

- G_S - Sample and hold board gain in proportional parts (10)
 G_D - Meter resistive divider ratio in proportional parts
 (68/3068)

Current meter calibration is accomplished by the variable resistance R22 on the current sample and hold board. The zero offset voltage of M3 is reduced to zero by adjusting R21 for zero meter reading with zero signal into the sample and hold board.

The voltage offset of the operational amplifier on the metering board is reduced to zero by adjusting R6 for zero meter reading with zero signal into the metering board.

Voltage Metering

The voltage across the load is applied to a 25 to 1 voltage divider formed by resistors R10 and R11 on the preamplifier board. The gain of the metering amplifier is 0.2 determined by the 200 kilohm feedback resistor and the 1 megohm input resistor. The voltage indicating panel meter reads 100 volts full scale and is converted to 0.2 volts across the meter as follows:

$$V_E = V_{FS} G_{VD} G_M G_S G_D = 0.177V$$

where

- V_M - Meter reading in volts (proportional to voltage)
 V_{FS} - Full scale voltage in volts (100V)
 G_{VD} - Voltage divider ratio in proportional parts (0.04)
 G_M - Metering board gain in proportional parts (0.2)
 G_S - Sample and hold board gain in proportional parts (10)
 G_D - Meter resistance divider ratio in proportional parts
 (68/3068)

Voltage meter calibration is accomplished by the variable resistance R22 on the voltage sample and hold board.

VI CONTROL LOGIC

The control logic, Figure 17, satisfies requirements 5 and 7 performing the following functions when the operator pushes the start button.

1. Removes the short across the Integrating capacitor so the ramp can start.
2. Switches the cross point scanner relays, Figure 18, page 36, which transfer the resistors being anodized from the main system to the pre-anodizer.
3. Switches the current and voltage sample and hold circuits to the sample mode.
4. Detects when the desired V maximum is reached and terminates the cycle by reversing the operations performed in 1 and 2 above.
5. Terminates the cycle if the ramp never reaches V maximum due to the load being too low in impedance. This is done on a time out signal from the Integrator as described in Subsection IV.

The logic circuits were designed using Transistor-Transistor-Logic (TTL) type logic elements, Texas Instruments Inc. (8) and Hill and Peterson (9). The circuit used to do most of the switching is the set-reset flip-flop formed by cross coupling two NAND gate sections of an SN7400 as in the NAND gates of U1 connected to the remote start control. The most desirable feature of this circuit is that if one of the inputs is held at logic high (+5V) the state of the flip-flop is changed by the first negative transition (logic low or zero volts) on the other input. Any further positive or negative transitions on that input cause no further changes in state thus eliminating any problems of switch bounce. The flip-flop is reset by removing the logic low from one input and applying a logic low to the other. The flip-flop can be connected to reset itself after a time delay to produce one pulse of a selectable width in response to a fast logic low pulse as with the NAND gates of U2. Here a fast negative transition on pin 1 of U2 sets pin 3 to a logic high, which is applied to pin 4. This logic high and the logic high on pin 5 supplied by pin 11 cause pin 6 to go low. The low on pin 6 is inverted to a logic high at pin 8 but the resistance-capacitance time of capacitor C3 and the output

Figure 18. Crosspoint scanner PCB assembly

Impedance of U2 at pin 8 prevents pin 8 from going high for approximately 1 resistance-capacitance time. When it does go high the high is inverted by U2 at pin 11 which provides the low required at pin 5 to reset the flip-flop.

The logic inverters SN7406 were used because their outputs are transistors with no internal collector loads. The outputs of any number of them can be connected together with a common resistor to +5 volts to form what is called a "wired-or" function. With this connection any of the Inverter outputs can pull the common output line to a logic low.

The status switch has a detent in position 1 for preanodizer in, a momentary contact at 2 and a detent in position 3 for preanodizer out. This switch insures that the preanodizer starts with all the set-reset (RS) flip-flops in the proper state. It also transfers the operator start switch through S1 in position 3 to the main system and disconnects the main system start from the preanodizer start through S2. The function of sections S3, S4, S5 and S6 will be described later.

The operation of the logic board is as follows:

1. A logic low from the start button is applied to printed circuit connector pin W causing pin U1-8 to go to logic low. This logic low is formed into a fast negative transition by C1, R2, and R3. Releasing the start button resets pin 8 to a logic high.
2. The fast negative transition formed by C1 is applied to pin 1 of U2 causing a 3 millisecond logic high at pin 3 of U2 which when inverted at pin 2 of U3 provides the strobe signal necessary to switch the relays and transfer the load. The 3 millisecond logic low at pin 6 of U2 is applied to pin 1 of U1 setting this flip-flop to logic high at pin 3 of U1 to signal the start of meter sampling. The logic low at pin 6 of U1 removes the short across the integrating capacitor to start the ramp and provides the logic level necessary to direct the load switching relays to the proper state.
3. The fast negative transition from C1 is also applied to pin 9 of U4 resetting this flip-flop, if it were set by a time-out from the last cycle. This flip-flop controls the dV/dt error light.
4. Operational amplifier U7 forms a comparator which compares the ramp voltage (divided by the 25 to 1 voltage divider as it is applied to the

voltage measuring circuit) and the voltage at the tap of the V maximum control. When the ramp voltage reaches and exceeds the V maximum setting, the output of U7 goes to logic high which is inverted to a logic low at pin 8 of U3. This logic low is applied to pin 5 of U1, resetting this flip-flop which terminates the ramp and places the metering circuits in the hold condition. If the ramp never reaches the V maximum setting a signal at the time-out pin P inverted at pin 10 of U3 performs the reset function. This signal also is applied to pin 13 of U4 setting this flip-flop which lights the dV/dt error light indicating that a normal ramp did not occur.

5. The load is not transferred from the preanodizer to the main system until the output ramp has decayed from its negative value back up to a voltage very close to zero as detected by the comparator formed by operational amplifier U6. When this occurs the flip-flop formed by U5 produces a 3 millisecond strobe pulse at pin 8 which is inverted at pin 6 of U3. This inverted pulse strobes the load switching relays so that they return the load to the main system. This inverted pulse also provides the start pulse for the main system through S2 of the status switch.

The preanodizing cycle is now complete and the unit stands by waiting for another start from the operator.

When the preanodizer is switched out by the status switch the following functions are performed.

1. The start button is connected to the main system through S1.
2. The start from the preanodizer to the main system is disconnected by S2.
3. S3 In position 2 provides a relay strobe by completing the base circuit of Q1 to ground. At the same time position 2 of S4 applies a ground to pin 4 of U1 forcing pin 6 of U1 to a logic high. This gives the load relay the address to transfer the load to the main system and signals the integrator to terminate any ramp it has started.

4. Position 2 of S5 holds the metering sample boards in "sample" so they can follow the terminated ramp to zero. Position 3 of S5 then locks the meters in the hold position.
5. Position 3 of S3 insures that the flip-flop controlling the dV/dt error light is held in its reset condition with the light out.
6. S6 holds the flip-flop formed by pins 1 to 6 of U1 in its reset condition which is a low on pin U and a high on pin T of the printed circuit connector.

CALIBRATION AND FINAL EVALUATION OF PREANODIZER

A calibration procedure was written for manufacturing checkout and customer use. Final evaluation was made after calibration of ten production units all of which met the necessary requirements.

The calibration involves adjusting the unit from the output meter circuits back toward the input integrator circuit. This insures that each section is in proper adjustment before its preceding section is added. The calibration is performed as shown in Figure 19.

EQUIPMENT REQUIRED or equivalent:

DC Voltmeter $\pm 1\%$ accuracy
Oscilloscope $\pm 3\%$ accuracy

1. Connect all cables except the ac line cord and the leads between the binding posts on the preamplifier output and the multiplexer.
2. Set the SELECTOR switch to the IN position and check the following dc voltages on connector J1, measuring with respect to Pins 11 and 12: Pin 8 = $+15 \pm 0.1$ V, Pin 9 = -15 ± 0.1 V, Pin 10 = $+5 \pm 0.1$ V.
3. Remove circuit board A4 (logic board; ESI Part No. 27101) and connect a jumper on the board connector from Pin Z to Pin U. Note that the IN PROCESS light is ON.
4. Remove circuit board A7 (voltage sample and hold; ESI Part No. 23069) and short the terminals of the VOLTAGE meter. Adjust the mechanical zero if necessary. Remove the meter short and replace the circuit board.
5. Remove circuit board A6 (current sample and hold; ESI Part No. 23069) and short out the CURRENT meter. Adjust the mechanical zero if necessary. Remove the meter short and replace the circuit board.
6. Remove circuit board A5 (metering board; ESI Part No. 2360T) and connect jumpers on the board connector between Pins E and Z and between Pins N and Z.
7. Adjust trimmer R21 on circuit board A7 for a zero reading on the VOLTAGE meter. Adjust trimmer R21 on circuit board A6 for a zero reading on the CURRENT meter. Remove jumpers and replace circuit board A5.
8. Remove circuit board A2 (preamplifier; ESI Part No. 27146) and connect jumpers on the board connector between Pins 10 and R and between Pins 7 and R.
9. Adjust trimmer R5 on circuit board A5 (metering board) for a zero reading on the VOLTAGE meter. Adjust trimmer R33 for a zero reading on the CURRENT meter. Remove the jumpers and replace circuit board A2.
10. Remove jumper from circuit board A4 connector and replace A4 (logic board; ESI Part No. 27101). Put circuit board A2 (preamplifier) on an extender and connect ac line cord to an ac outlet.
11. Measure the dc voltage with the oscilloscope connected to junction of CR6 and R11 on the preamplifier board. Adjust the average dc level to -0.6 volts with trimmer R8 on circuit board A3 (integrator). There is approximately 0.2 V p-p ripple at this point which is normal for a no-load condition; adjust the -0.6 V level to the center of the ripple. Remove the extender and replace circuit board A3.
12. Remove the extender and replace circuit board A3. Place circuit board A4 on the extender and connect the oscilloscope to the OUTPUT binding posts with the scope ground lead connected to the "+" binding post and the scope probe to the "-" binding post. (NOTE: oscilloscope must be floating.)
13. Connect the external sync input of the oscilloscope to Pin U of circuit board A4 (logic board). The signal of Pin U provides a positive-going logic level transition at the beginning of the voltage ramp cycle. Set the oscilloscope time base for 0.5 s/div. and the vertical sensitivity for 20 V/div.
14. Set the V_{max} control to 80 V and the dv/dt control to 2400 V/min (these settings will result in a 2 s ramp). Start a ramp cycle by pressing the REMOTE START button, then adjust the V_{max} trimmer (located behind the front panel near the CURRENT meter) for 80 ± 2 V as measured on the oscilloscope. Ramp time should be $2 \pm 1\%$ and is factory set by selection of R6 on the integrator board. Repeat cycle as required.
15. After completing step 14, adjust trimmer R22 on the voltage and sample board (A7) for 80 V on the VOLTAGE meter. It may be necessary to repeat the cycle several times to make this adjustment.
16. Connect a $30 \Omega \pm 1\%$, 20 W resistor to the OUTPUT binding posts. Set the oscilloscope time base for 0.1 s/div. and the vertical sensitivity to 5 V/div.
17. Adjust the V_{max} control for 30 V. Start the ramp cycle and adjust trimmer R22 on circuit board A6 (sample and hold) until the CURRENT meter reads 1 A. Repeat the cycle as needed.
18. Remove the 30Ω resistor and connect a short across the OUTPUT binding posts. Adjust the dv/dt control to 100 V/min and start a ramp cycle. Current should rise to approximately 2 A (first current limit), then drop to less than 1 A (second current limit). The dv/dt error light should come on at the end of the ramp cycle.

Figure 19. Calibration procedure

CONCLUSION

The design of the preanodizer described in this thesis was an interesting experience which required study in several areas of electronic technology. These areas included:

1. Power supply design
2. Signal generation
3. Power amplification of the generated signal
4. Metering circuit design
5. Logic and control circuit design

Each section required a search of current literature for suitable electronic circuits and devices. The courses taken while fulfilling the Master's Degree requirements were necessary for this project. The ability to approach a project of this complexity would have been very difficult without the courses in electronics, logic design, and mathematics taken at Portland State University.

Since there are many different ways to accomplish a given task the final choices were made on a basis of the highest reliability and optimum performance. After the circuit design decisions were made, many of the circuits had to be built and tested prior to a final choice. Several design changes were made as a result of these tests.

The author's project responsibilities extended from the circuit design stage through hardware design into the production phase and then into final test and calibration.

After completion of the design a production run of ten units was made, tested and shipped to the Western Electric Company. These units have been in service for approximately two years and as of this date none of them have experienced a failure.

Future projects assigned to the author will certainly benefit from the knowledge and experience gained on this project.

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