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Digital Control in Tube Power Amplifiers

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Digital Control in Tube Power Amplifiers

by

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Digital Control In Tube Power Amplifiers

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August 2010

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Abstract

Vacuum tubes are an old technology with a very important use in the audio electronics industry. They have a comparatively short life cycle and must be replaced often. This is a burden for the consumer since they must then calibrate (bias) the new set of tubes. This exposes the consumer to potentially lethal voltages. If the bias is not set correctly the tubes could be destroyed or the amplifier could operate inefficiently.

The work presented in this thesis describes a digital control system that maintains optimum biasing for any tube used in the power amplifier. This system automatically determines the ideal bias voltage every time the amplifier is turned on. Unlike other designs, this system is completely non-intrusive and does not affect audio quality. The system requires no consumer maintenance and has nearly eliminated the burden of replacing the tubes in an audio power amplifier.

Acknowledgements

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Chapter 1 Introduction

1.1 History

Vacuum tubes are the predecessor to the modern transistor. Before the 1960's they were used in nearly every electronic device; televisions, radios, and computers. There are several different types of vacuum tubes: diodes, triodes, tetrodes, and pentodes. Diodes and triodes are typically used for rectification and small signal amplification, whereas tetrodes and pentodes are used for power amplifiers (audio speaker drivers, radio transmitters, and microwaves). The task of a power amplifier is to provide a fixed level of gain to a processed signal and deliver power into a load such as a loudspeaker [1]. For the purposes of this work, a tetrode is the same as a pentode, and both will referred to as power tubes. Most power tubes have been replaced by the modern transistor, although these tubes still hold a very important application in the audio amplifier industry.

1.2 The Problem

Audio amplifiers based on power tubes have become increasingly popular in the past ten years despite the large production of solid state (transistor) amplifiers. This is because they produce purer sounds which are more pleasing to the human ear. Tube audio power amplifiers are used almost exclusively by pro guitarist and bass players. These amplifiers are used at nearly every professional music production and recording studio. Power tube production in the world is very limited as the vast majority of them are manufactured in Eastern Europe and Russia, in facilities that have been in operation since the 1940's. This variance in production creates very unpredictable results in terms of sound quality making it difficult for high end audio manufacturers to have consistent and favourable production quality. Power tubes by nature run at very high temperatures. The thermal stress will change the alignment and shape of metal components in the tube. This will inevitably change the operating characteristics of the tube over its lifetime. Since it is not possible to change the way these tubes are being used and manufactured, circuits must be designed to be adaptive to accommodate this variance and allow each amplifier to run optimally.

Chapter 2 Background and Literature Review

2.1 Introduction

In this chapter the fundamental operation of power tubes will be reviewed along with a review of prior research. This review will give a fundamental understanding of the basic concepts that will be used with the adaptive circuit design developed in this thesis. The amplifier constructed for testing the adaptive circuit is also examined as each component of the amplifier is directly linked to the adaptive biasing circuit.

2.2 Operation of Power tubes

Power pentodes (see Figure 2.1) are five terminal devices that are used to amplify power and drive loudspeakers. The five terminals are the Anode, Cathode, Grid, Screen Grid, and Suppressor Grid. There are also two terminals for the heater, which is used to heat the cathode allowing the thermionic emission. There are many resources available on the physics of pentode operation, therefore a very simple overview is provided for understanding of the material in this thesis.

When the cathode of a power pentode is heated a cloud of electrons form around it. The electrons will flow towards the positively charged anode and screen grid. A grid is placed between the cathode and the anode/screen grid to control how many electrons flow. If the grid voltage is very negative no electrons will flow. If the grid voltage is close to 0 V, many electrons will flow. By modulating the grid voltage you can vary the large anode current and produce amplification. Most of the electrons from the cathode go to the anode, while approximately 10% of them go to the screen grid. Although the real physics of a power pentode are slightly more complicated, this explanation will provide a good basis for DC biasing. Note that the only difference between a pentode and a tetrode is that a pentode has a suppressor grid to mitigate parasitic capacitance. In terms of DC calculations, they can be treated as the same device.

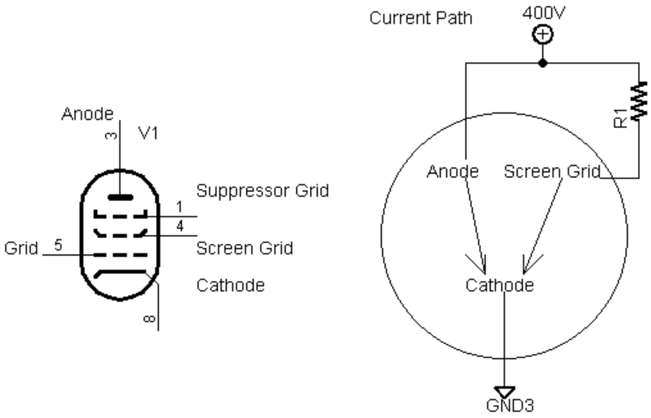


Figure 2.1: Terminals and Current Paths of a Power Pentode

2.2.1 Bias Types

Each power tube requires a DC bias voltage to function correctly. A bias voltage is applied between two terminals of the tube and essentially controls how much power the tube is going to consume/deliver at idle. If the bias is too high, the tube will overheat and inevitably destroy itself. Where as if the bias is too low, the output signal will be weak and the tube will run inefficiently. A perfect bias point must be found to ensure that the power tubes are running safely at their full potential. Audio amplifiers today use three topologies for biasing; each with their inherent problems:

Preset Bias Designs

Preset bias designs are not adjustable by the user and the bias point is the same for every tube used in the amplifier. The grid voltage is fixed, and valve current is determined purely by valve characteristics, so there is no protection against over-current, or compensation for changes in valve characteristics with age [1]. This is generally a poor scheme as all tubes have inherent variances from manufacturing. In order for them to run optimally each tube needs a uniquely calibrated bias voltage.

Adjustable bias designs

Adjustable bias designs mitigate the previous problem by allowing the consumer to adjust the bias voltage with a set screw or knob system. This allows the power tubes to run within safe limits, however the bias point may not be optimal since it was selected by the consumer. This topology can also be very dangerous as the consumer is required to disassemble the amplifier and monitor high voltages (>400 V) while the system is fully powered. Since the life span of a power tube can be short, this must be done every time the tubes are replaced. This can be quite the burden for the consumer. Another option is to send the amplifier back to the manufacturer for tube replacement and calibration, though very few will do this as it is quite costly.

Cathode Bias designs

Cathode biased designs use an AC bypassed power resistor to set a positive voltage at the cathode. The grid of the tube is DC grounded so the grid to cathode voltage still remains negative. This topology has a self limiting feature; as the cathode current increases, so does the bias voltage, hence decreasing the cathode current. This type of bias is very inefficient and generally results in a less than 50% power output ratio. This is mainly contributed to the large loss of power in the cathode bias resistor.

2.2.2 Optimum Bias Point

The optimum bias point for a pair of power tubes in push-pull configuration is 70% anode dissipation at idle. This value has been determined experimentally and is the industry standard ‘rule of thumb’. Biasing an amplifier at or above 80% dramatically decreases the tubes lifespan, while biasing at or below 60% produces a noticeably weak audio power output.

Biasing at idle means that when there is no AC signal applied to the tube grid, the power dissipated in its anode is 70% of its maximum dissipation rating. For Example, EL34 tubes have a maximum dissipation rating of 25 W. This mean that at idle they should dissipate 0.70 x 25 W = 17.5 W. So if a pair of EL34s is running at 400 V the idle bias current should be set to 17.5 W/400 V = 43.75 mA per tube or 87.5 mA total. Note that this is the value of the anode current, which is not the same as the cathode current (cathode current is the sum of the screen current and anode current).

2.2.3 The Screen Grid

Screen grid current must be subtracted from the cathode current to get the true anode current (and hence the true anode dissipation). Screen grid current varies depending on the screen grid resistor, the screen grid voltage, and the transconductance of the tube. The screen grid current is typically 5%-10% of the anode current. This is treated as a known constant since the screen grid current variance amongst tubes for a given condition (supply voltage/screen grid resistor) is negligible.

2.3 Literature Review

There has been no prior research in digital control for tube audio power amplifiers specifically, however there have been a number of papers done on projects with similar aspects. These papers are summarized below.

2.3.1 A Simple Direct-Coupled Power MOSFET Audio Amplifier Topology Featuring Bias Stabilization

This paper [2] introduced an automated bias control for a 200 W MOSFET audio power amplifier; this was at a time when FET power sections were new. The automated bias control was needed to stabilize the large temperature variance inherent in FETs. So although this is not a tube amplifier, both devices can change their operating characteristics over time and between devices. The bias scheme presented does not possess memory and therefore must continuously be sampling the FET current. The authors showed that it is somewhat difficult to sample the DC current since there is a large AC current swing present when the amplifier is in use. Overall the circuit had good performance, but it was intrusive since it always had the sampling circuitry in the audio signal path.

2.3.2 Class AB Large Swing CMOS Buffer Amplifier with Controlled Bias Current

This paper [3] presented an automated bias control for a 4.7 mW 1.2 μm CMOS buffer amplifier. This amplifier was designed to drive telecommunication lines at voice frequencies and uses continuous sampling and a DC servo to control the CMOS bias current. The major difference with this approach is that it is built on an integrated circuit so a different sampling approach was used. In this case the authors used a diode connected transistor to sample the current. Once again this circuit performed well but utilized intrusive sampling.

2.3.3 Digital Control System for the Thermionic Cathode in an Electron Gun

Though not directly related to audio electronics, this paper [4] presents a modern digital control system for a thermionic cathode (audio tubes also use thermionic cathodes). The authors used a microprocessor to control the current in the cathode to prevent it from destroying the electron gun. The system uses a photo-sensor to sample the current which is then sent through an analog-to-digital converter (ADC) and processed by the microprocessor. The output is sent through a digital-to-analog converter (DAC) and is used to control the cathode’s heating source. This system is analogous to what will be used for audio tubes except that this system utilizes continuous sampling (which is acceptable for electron gun applications). This paper demonstrates how a microprocessor can be used to intelligently control a closed loop system.

2.4 The Reference Amplifier

In order to test the proposed adaptive circuit, a reference amplifier is constructed.

2.4.1 System Parameters

This amplifier was designed to accommodate the three different tube types available. The test fixture consists of a push pull power amplifier including a phase inverter/driver circuit for ease of testing. Table 2.1 is a summary of the requirements for the different tube types. The test fixture is designed around these parameters.

Tube Type	KT77	6L6	EL34
Supply Voltage	800 Vmax	500 Vmax	800 Vmax
Anode Dissipation	25 W	30 W	25 W
Reflected Impedance	~3200 ohm	~3400 ohm	~3200 ohm
Heater Current	1.4 A	0.9 A	1.5 A
Screen Voltage	800 Vmax	450 Vmax	450 Vmax
Rg2	1000 ohm	1000 ohm	1-2 kohm
Bias Voltage	-10 V to -40 V	-10 V to -40 V	-10 V to -40 V

Table 2.1: Requirements for the Different Tube Types

2.4.2 Power Supply

The power supply was designed to accommodate the maximum supply loads. In this case an anode supply voltage of 400 V was targeted. This is suitable for all the tube types and is a typical anode voltage in musical amplifiers with these types of tubes.

The appropriate supply current was determined by examining the maximum load amongst the tubes. Each 6L6 is capable of dissipating 30 W. This requires 30 W / 400 V = 75 mA per tube. Therefore the power supply was designed for 200 mA, the extra 50 mA is used to accommodate preamp circuitry and screen grid currents.

A Hammond 272HX was chosen to meet these requirements. The 272HX has a 600 VCT winding that can accommodate 200 mA [5]. It also has a 6.3 VCT winding that can accommodate 6 A, this winding is used for the heaters.

The power supply has 3 voltage points: a main anode voltage of ~400 V at 150 mA, a screen grid voltage of ~380 V at 20 mA, and a phase inverter voltage of ~320 V at 2 mA.

It is important to note that these are just target voltages and that they will change depending on which tube is loading the supply.

A negative voltage power supply is needed to bias the grids of the power tubes from -40 V to -10 V. This is done with a half wave rectifier from the main high voltage winding. A half wave rectifier is used for simplicity since the current draw from this source is very small (very little current will flow into the power tube grids). A capacitive network and a linear potentiometer are included to manually adjust the bias voltage. This potentiometer will later be replaced by the output control circuit from the microcontroller.

A low voltage power supply is needed to operate the microcontroller, relays, op-amps, and other ICs. The total load for this supply varies depending on how many relays are active, though the worst case load does not exceed 1 A. A bridge rectifier is used in conjunction with a fixed 5 Volt regulator to provide a constant and stable supply voltage under varying load conditions [6]. Initially this network was connected to the extra 5 VAC supply provided by the 272HX. Unfortunately the regulator input voltage was not high enough to be stable in all conditions. The network was connected to the 6.3 VAC heater winding to provide a higher regulator input voltage and a constant 5 V output.

A mains fuse is included in this test fixture for safety and protection purposes. At full load the amplifier will be drawing approximately 200 mA x 400 V = 80 VA from the main winding and 3 A x 6.3 V + 1 A x 5 V = 23.9 VA from the heater winding. The total normal load is thus ~100 VA. A 2 A fuse was chosen for the transformer primary, this will activate if the circuit draws approximately twice of its normal VA rating and will provide good protection against faults. Figure 2.2 shows the power supply design.

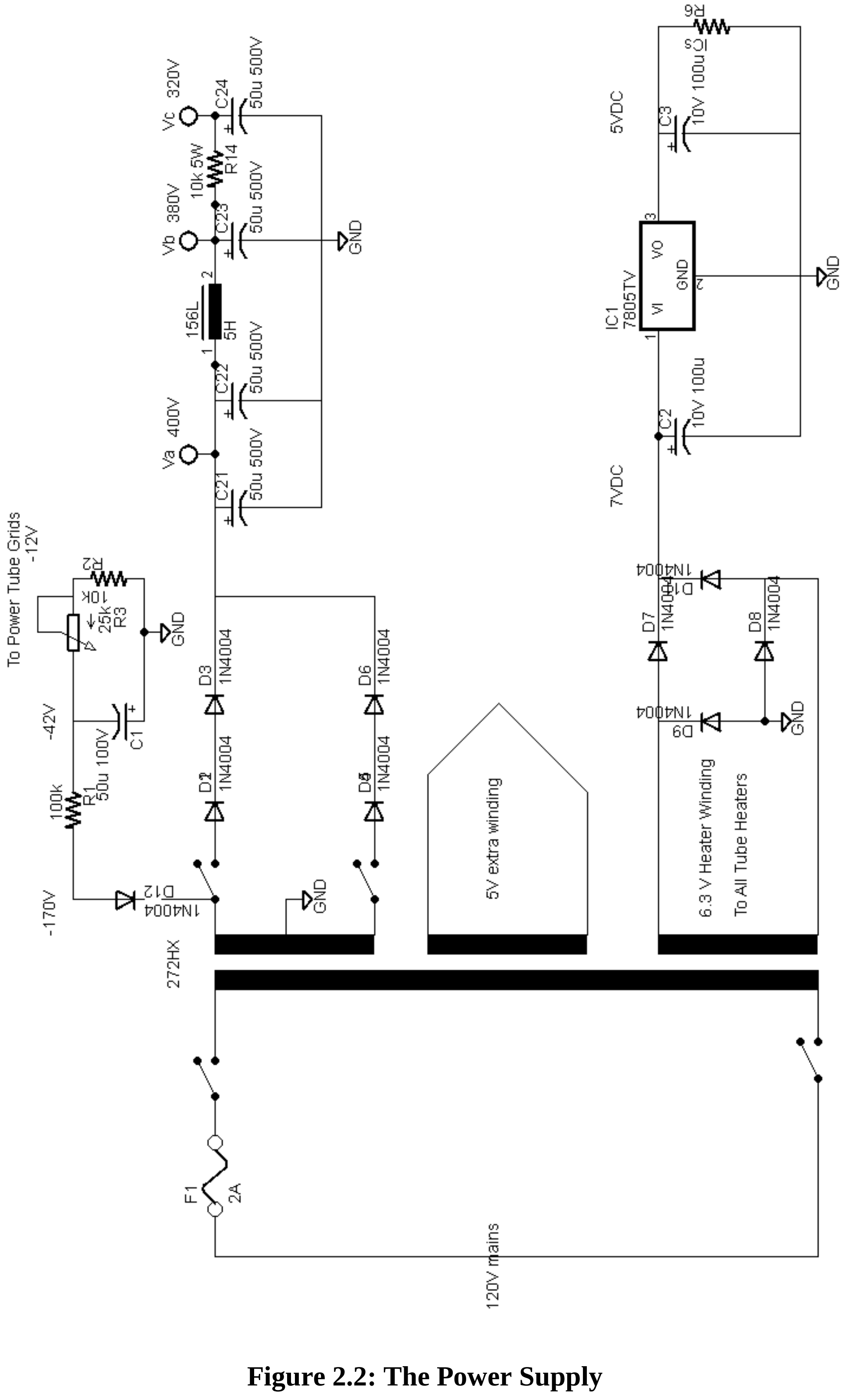


Figure 2.2: The Power Supply

2.4.3 Output Stage

Unlike transistor amplifiers, tube power amplifiers require an output transformer to couple the power from the high impedance power tubes to the low impedance speakers. Tube amplifiers are sensitive to impedance matching. An unmatched load will operate the tube in an unsafe dissipation region and will cause its destruction. For this push pull stage an output transformer was chosen that can accommodate the three different tube types. The 6L6, EL34, and KT77 have similar requirements (3200 ohm) .The Hammond 1750N is ideal for this application. It has a 3200 ohm primary and a 4-8-16 ohm secondary [7]. It can handle 50 W of continuous audio power which is well suited for this high power amplifier

2.4.4 Phase Inverter

The phase inverter is necessary in a push pull amplifier as it delivers signals of opposite phase to each of the power tubes. The phase inverter also acts as a driver as it amplifies a line level signal up to the point where it can drive a power tube grid. The details of phase inverter operation are quite lengthy, so they will not be discussed in detail. A standard “long tail phase inverter” design was chosen and attached to the power section as shown in Figure 2.3.

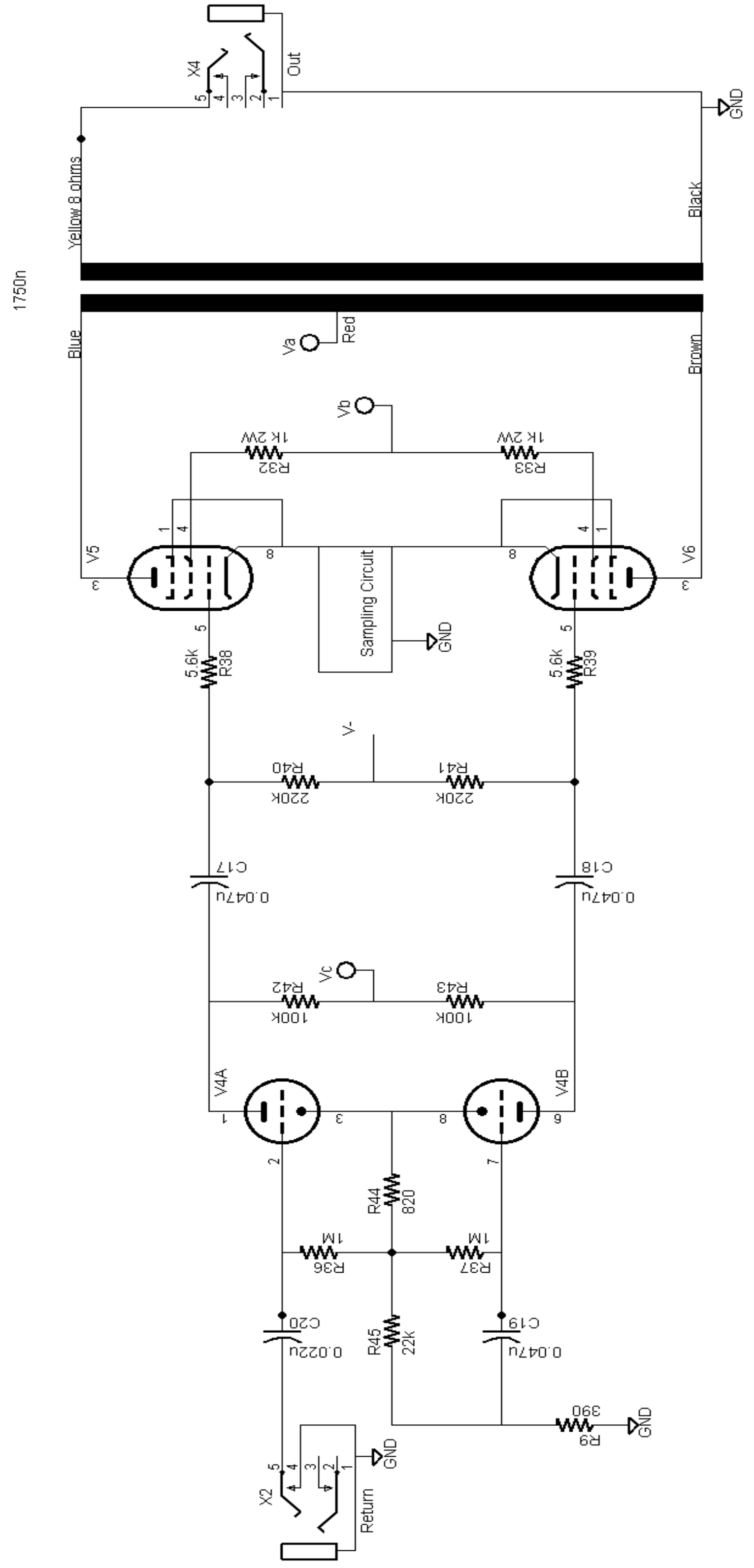


Figure 2.3: Test Fixture Schematic

Chapter 3 Designing an adaptive circuit

3.1 Introduction

This chapter examines the design of the adaptive bias circuit. The hardware design is presented followed by the software design. Each step of the process is detailed, including the background research and unsuccessful designs.

3.2 Control Circuit types

The main challenge of this work is to design a circuit that will hold the bias voltage at an optimum point. The exact point should be easily configurable so that so that it will function with a range of supply voltages. The following are several possible approaches to explore in designing this circuit.

DC Servo Control Circuit

This is the simplest approach to implement as it involves continuous monitoring of the tubes cathode current and instantaneous adjustment (using op-amps and analog circuitry). This type of bias control is already implemented in modern amplifier design [2]. The main problem is that it involves continuous sampling which induces a load on the power amplifier which produces unfavourable audible results. The goal of this thesis is to produce a totally transparent circuit, therefore a different approach is required.

Analog Sample and Hold

This approach requires sampling the cathode current and holding its value in an analog network; generally through capacitors. The sampling circuit can then be disconnected from the power amplifier therefore solving the prior transparency issue. The held current value can be used to adjust the bias voltage using analog computation. This approach would have been feasible when microprocessors were relatively expensive and overall costs were high., Today however it is the opposite where the cost to implement the analog computation and holding circuitry far exceeds that of the cost of microprocessor.

Microcontroller Sample and Hold

The final approach requires using an ADC to store and process the cathode current value in the microcontroller. The microcontroller can use an algorithm to determine how the output bias voltage must change. The microcontroller will continue sampling this value until it determines what output value it should hold. Once all the computations and comparisons have been made, the microcontroller can activate a transparency relay and detach the sampling circuitry from the power amplifier. This method also has the advantage of making intelligent control decisions. For example, it is easy to implement a failure detection circuit as it would simply require a few lines of code. Other intelligent features can easily be added to the system as the microcontroller can be reprogrammed with simplicity. This avenue is not always easy with analog control circuits as it generally requires a physical change to the circuit.

3.3 Designing the Circuit

It was decided to use the microcontroller circuit as it offers the most promise, expandability, and minimal cost.

3.3.1 Signal Processing Algorithm

The signal processing algorithm is a basic feedback loop. The system examines the input value and compares it to a range of ideal values. If that input value is not within the range of acceptable ideal values, then the microcontroller adjusts the output accordingly. Once the input value is ideal, the microcontroller stores the resulting output and detaches the sampling circuit from the power tubes. This stored value will be used as a starting point each time the amplifier is turned on. Figure 3.1 shows a flow chart of this algorithm.

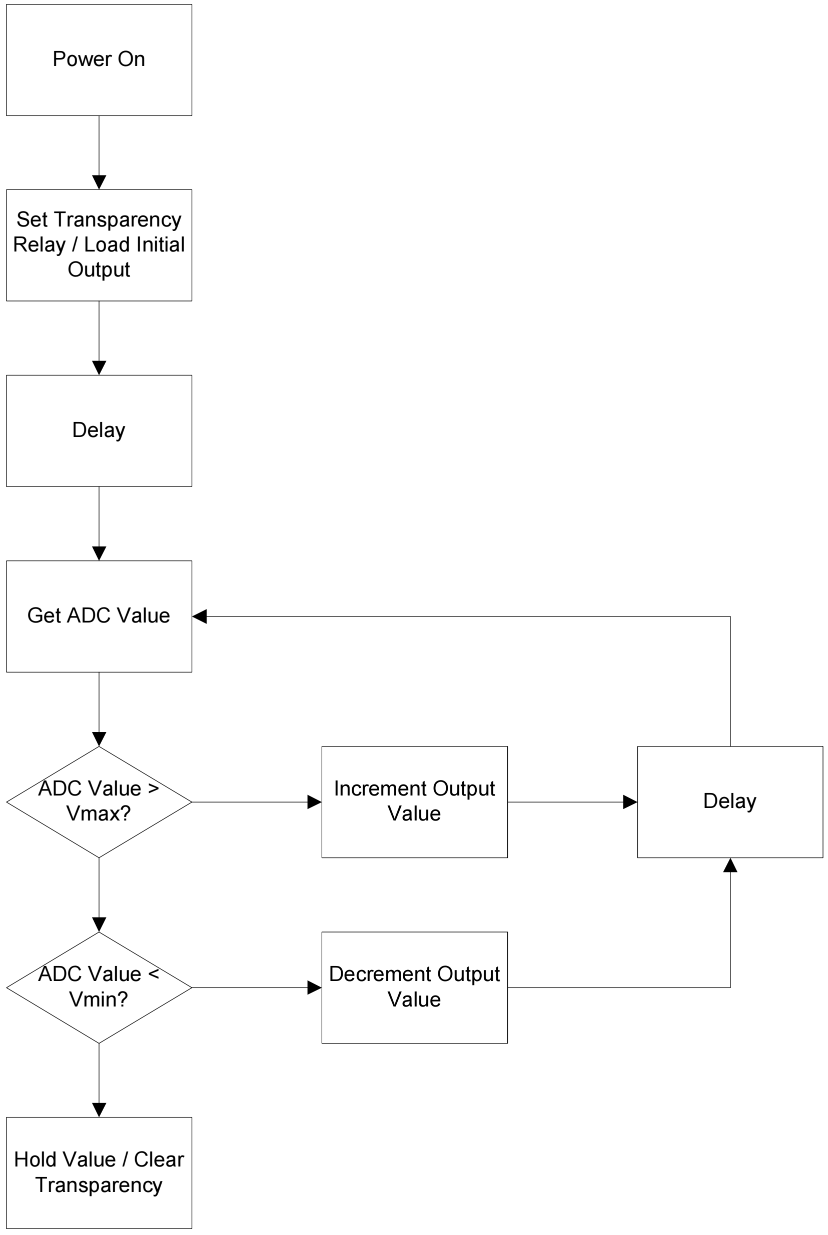


Figure 3.1: General Algorithm

3.3.2 The Sampling Circuit

The sampling circuit consists of a very small and accurate resistor tied to the cathode of both power tubes in the amplifier. The resistor is bypassed by the transparency resistor when not in the sampling mode. It is important that the sampling resistor is small as a large sampling resistor will create inaccurate bias points when the circuit changes out of sampling mode. The reason for this is that the total cathode current path will have an extra resistance in series when sampling. A 1 ohm resistor is suitable and will not significantly change the bias current when not in sampling mode.

The combined DC cathode current will be somewhere between 70 mA and 140 mA for all types of tubes. This range accounts for anode dissipation between 50% and 100% of the max dissipation rating. With a 1 ohm sampling resistor the analog sampling signal will be between 0.07 V and 0.14 V.

The built-in ADC has an 8-bit sampling resolution which is linearly defined between 0 V and the microcontroller supply voltage of 5 V. This translates to an incremental resolution of 0.02 V. Based on the sampled voltage of 0.07 V to 0.14 V, this would only allow for 5 distinct input values. To increase the resolution of the input sampling, the signal is then multiplied by 34 and offset to obtain a signal between 0 V and 4.76 V into the ADC, thus using the full input resolution. Figure 3.2 shows the complete sampling circuit.

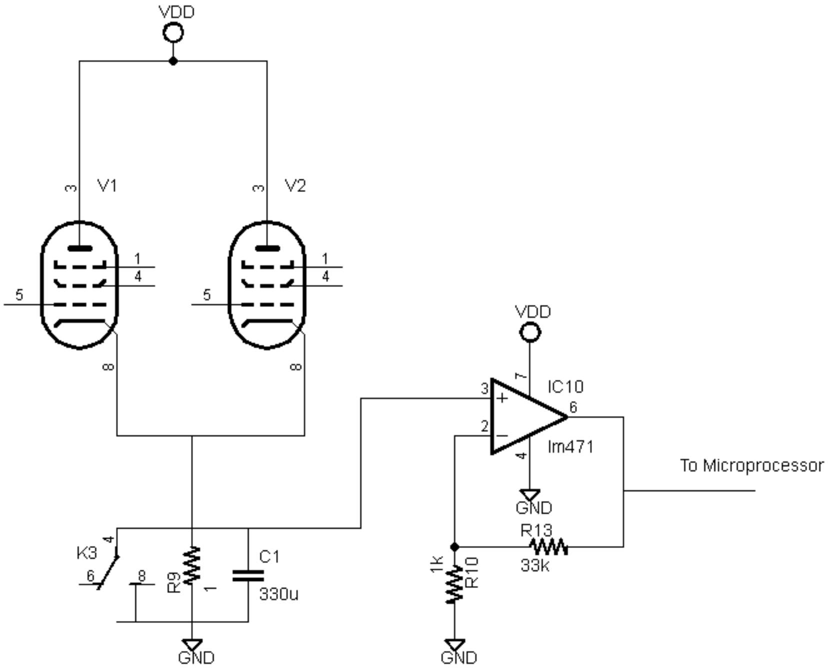


Figure 3.2: Sampling Circuit Schematic

3.3.3 The Transparency Relay

A high current relay is required to disconnect the sampling circuitry from the amplifier once a proper bias has been established. It must also bypass the sampling the resistor. Since it is bypassing the sampling resistor all of tubes current will flow through the relay. The relay must be able to handle 200 mA and have a dual pole, dual throw configuration.

3.3.4 Bias Voltage Output Types

The microcontroller control network must process the input sampling voltage and output a bias voltage for the power tubes. The bias voltage can range between -10 V and -40 V, and will be adjusted using a variable resistance. To control this voltage the microcontroller must be fully isolated from the high voltage negative supply. There are several different approaches to this:

High Voltage Digital Potentiometer

A high voltage digital potentiometer would be an ideal and simple solution to the isolation problem. Unfortunately the highest commercially available voltage rating is only 30V. Since the output bias voltage needs to go as low as -40 V this device could not be controlled by a digital signal between 0 V and 5 V.

This device could be used if it was placed under a different supply reference. For example, the ground of the device could be set at -40 V and the positive terminal at -10 V. This would allow full voltage control over the needed range while keeping the device within voltage limits. The problem unfortunately is that the digital control signals from the microcontroller must also be isolated into the -40 V to -10 V reference. This would have to be done with opto-couplers or solid state relays; a very costly requirement in hardware which is not feasible compared to the other approaches listed.

Motorized Potentiometer

A motorized potentiometer uses a DC motor to remotely control the wiper of a potentiometer. These devices are also very expensive and are difficult to control in order to obtain accurate results. It would also require a DAC to interface the motor to the microcontroller; a component not typically included within the microcontroller.

Opto-Coupler

Opto-couplers use a photo-resistor coupled to a LED to vary the output resistance based on how bright the LED is. Opto-couplers are relatively inexpensive but are too difficult to control accurately. These devices are typically either ON or OFF and the resistive range in between is very sensitive and varies greatly between components. These devices also require a DAC converter to interface to the microcontroller.

Power FET

An analog voltage signal can be applied to the gate of a power FET to control how much current it outputs. This current can then be used to create the bias voltage. This device would be difficult to control as it would depend on the very specific device curve traces of the transistor which are very nonlinear. It would also require a DAC converter to drive the gate signal.

Solid State Relays

Solid state relays can be used to bypass resistors in a string of resistance. This is very easy to do and does not require a DAC converter. These devices are inexpensive and can handle high voltages [8]. This string of resistors can be physically larger, however this is acceptable considering the size of the overall amplifier.

The solid state relays approach was chosen as it offered the best solution with the least possible problems. The relays were arranged in a chain to bypass different resistance values. This effectively changes the value of a resistive divider therefore adjusting the bias voltage. The overall resistance of the string needs to be ~25 kohm. If this is done with 8 different resistor values there can effectively be 256 different resistance values. Figure 3.3 shows the circuit while Table 3.1 shows the string of resistors values used in the design with standardized values which were very similar to the idealized requirements.

Resistor	Ideal Value	Closest Standard Value
R7	12 k	12 k
R6	6 k	6.2 k
R5	3 k	3 k
R4	1.5 k	1.5 k
R3	750	750
R2	375	390
R1	187.5	180
R0	93.75	91
Total Value:	23.9 k	24.1 k

Table 3.1: Resistor Values

When all of the resistors are not bypassed the total resistance is 24111 ohms.

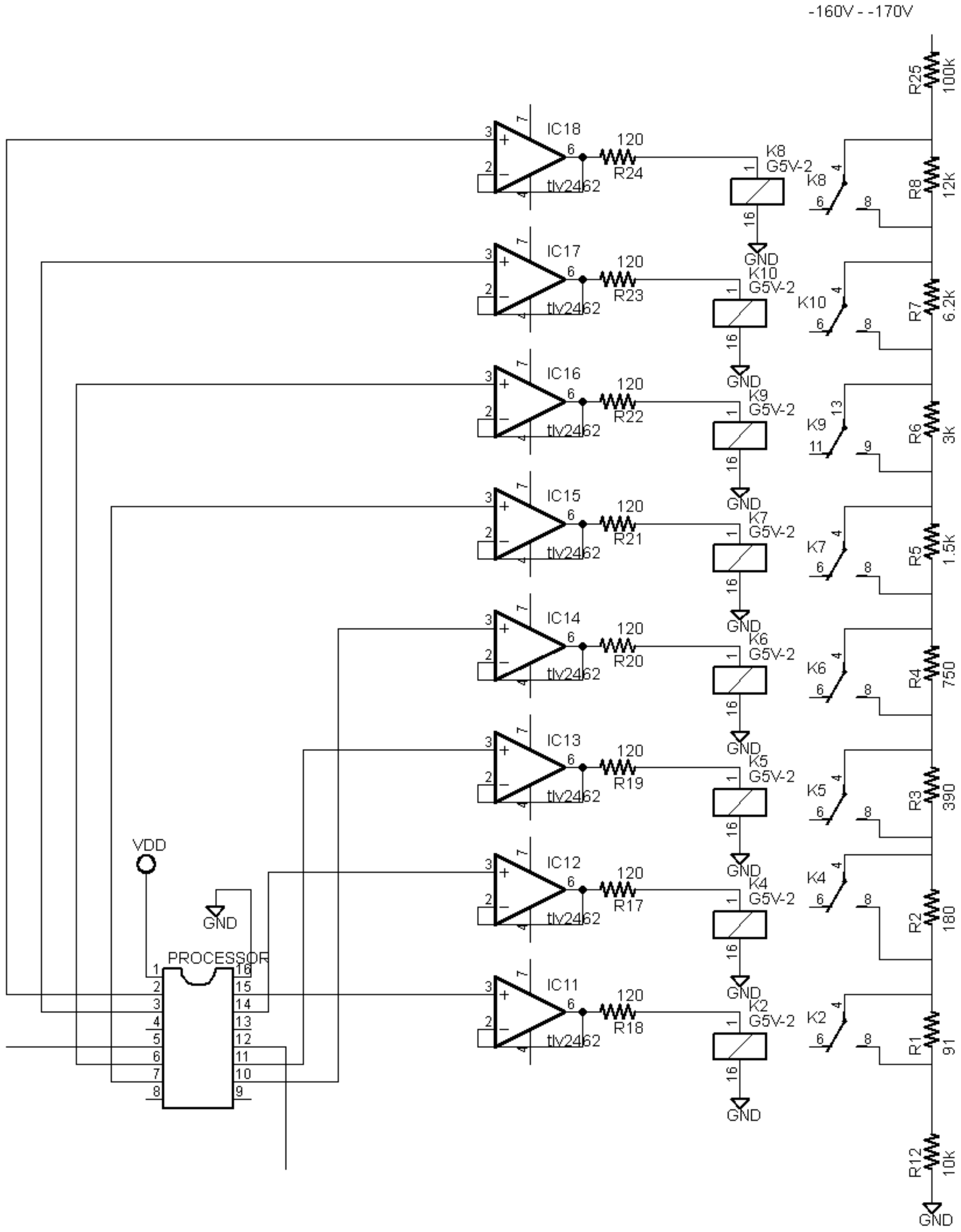


Figure 3.3: Relay Isolation Circuit

Some major problems were encountered while implementing the solid state relay design. When a mechanical relay is engaged the output shorts whereas a solid state relay enables current to flow through a triac. There is a voltage drop associated with current flowing through the output triac (about 1 V). This places an extra 1 V in the potential divider when a dead short is needed. This problem could be compensated for in software if it was not for the fact that solid state relays also latch. Essentially if a DC current is flowing through the output triac, it will not stop conducting until the input signal and the output signal cross zero (which never happens in DC). Unfortunately this means that once a relay is activated to bypass a resistor, it will not stop conducting regardless of what input is applied to it. This approach was deemed inappropriate and another attempt was made.

Mechanical Relays

Mechanical relays are slightly more expensive than solid state relays but provide true short and open switching (no latching, and no unwanted voltage drops) [9]**.** This approach was implemented using the same methodology as the solid state relay.

This mechanical relays approach was found to operate the best and was kept for the final design.

3.3.5 Screen Current Compensation

Screen grid current is usually assumed to be a fixed fraction of the cathode current. However there are slight variances in this fraction within each specific tube. This current should be sampled so that the anode current can be accurately calculated. At a fixed operating point, the screen current can deviate approximately +/- 1 mA between tubes. If a fixed value is used for the screen current the anode current will deviate +/- 1 mA. At the ideal operation point (70%) dissipation and a 400 V anode supply, this will vary the dissipation calculation by
1 mA x 400 V = 0.4 W, which is a total variance of 0.4 W/25 W = 1.6% for the EL34/KT77 and 1.3% for the 6L6. This is a small variance overall, so it is important that the hardware used to compensate for this is inexpensive in every sense otherwise the extra accuracy cannot be justified on a commercial basis.

Analog Sampler/Subtractor

A high impedance circuit was used to measure the voltage across the screen resistor (sample at two high voltage points). This voltage essentially indicated the screen current since the screen resistor is fixed at 1 kohm. High impedance voltage dividers were placed between the voltage points and ground. It is important that the network was very high impedance since it is essentially placed in parallel with the power tube. If the network was anything less than 10 Mohm it would have an effect on the sonic quality of the tube. The small voltage from the high impedance voltage dividers was then fed into buffers, and then into a differential amplifier to obtain a voltage difference. This voltage difference signal was then fed into another differential amplifier that subtracted the screen current from the cathode current to obtain the true anode current. This value was then sampled by the microcontroller.

The circuit functioned, but had too high of a variance to be useful. The inaccuracies in the op-amps and in the high impedance resistors (1% of 10 Mohms is 100 kohms) gave a range of variance that defeated the purpose of the circuit.

Digital Subtractor

This approach was very similar to the first except that it eliminated the differential amplifiers and their variance. The voltage divider signals were fed into buffers then directly to the microcontroller; the subtraction required was done in software. This approach had the disadvantage of using more microcontroller ports, however the variance associated with this circuit was improved, but still defeated the purpose of the circuit

Due to the high variances, neither approach was taken. Instead a fixed screen current value is assumed. The high impedance sampling is very difficult and expensive to perform accurately. More relay switching would be necessary to minimize the loading on the audio path by the sampling circuit. These screen sampling circuits were simply not accurate enough to justify the extra expense. Figure 3.4 shows the screen current compensation circuit while Figure 3.5 shows the sampling circuitry connected to the Development Board.

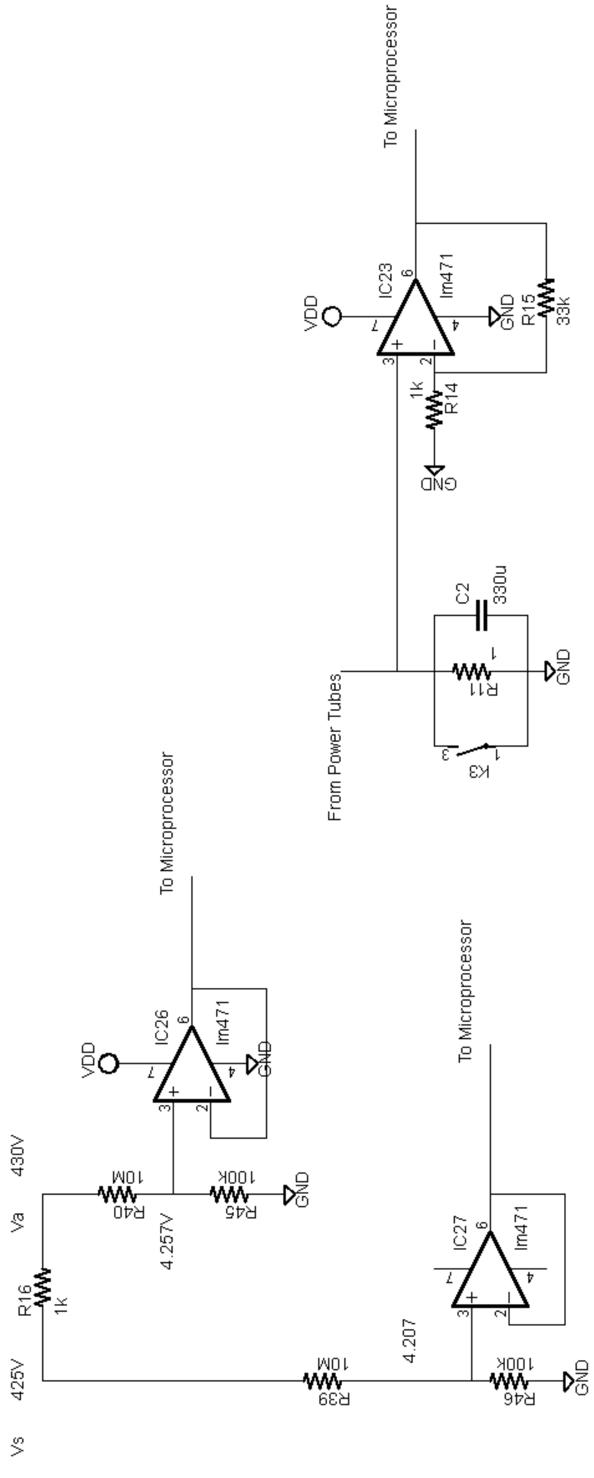


Figure 3.4: Screen Current Compensation Circuit

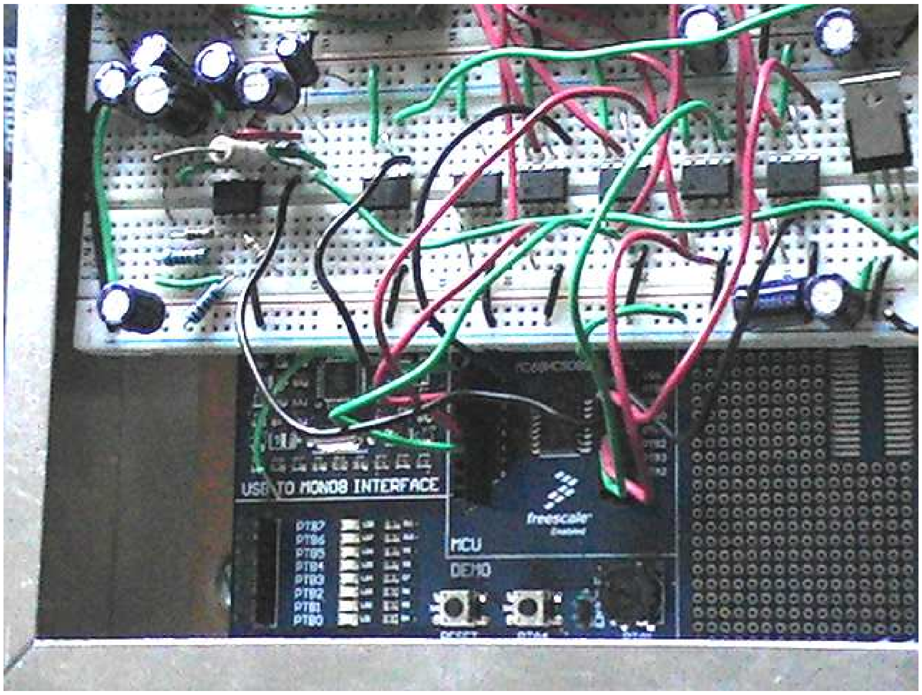


Figure 3.5: Microcontroller Development Board and Sampling Circuitry

3.3.6 Choosing a Microcontroller

With any commercial device, cost is a major consideration. In order to keep costs low, a microcontroller which meets the needs of the proposed circuit is selected. It has the following requirements:

- A built in ADC for sampling cathode current
- At least 8 output ports for controlling the bias voltage
- One output port for activating the transparency relay
- A USB interface for programming
- Speed is not critical, therefore it can be low to reduce cost
- Physical size is also not critical and can be sacrificed to further reduce cost

Considering these requirements, a Freescale MC68HC908QY4 was chosen. It is a low cost 8-bit microcontroller [10] that can be purchased in bulk for less than $2.00 a piece. For the prototype a Softec HC908 development kit [11] (pre-fabricated printed circuit board) will be used to program the microcontroller and to interface it to the amplifier circuitry.

3.4 Software Algorithms

3.4.1 Former Value Check Algorithm

The microcontroller contains 4096 bytes of non-volatile FLASH memory. Some of this memory is used to store the calculated output value from the last time the program was run. This gives a superior starting point, in many cases the program will not even need to perform any additional analysis. The ideal output value will not change dramatically between power ups, so the adjustment that has to be made will be small (or non-existent). This significantly reduces the amount of wait time required for this system.

The FLASH memory included on the MC68HC908QY4 cannot be programmed or erased when it is running user code from the flash memory [10]. The on-chip auxiliary ROM contains a built in routine for flash programming [12]. By using the built in routine PRGRNGE, any of range of FLASH memory can be programmed. In this case only one byte is necessary for the formerly calculated output value. Two bytes is the minimum programming space for this algorithm, so a dummy byte is included.

Immediately upon entry, the program checks the contents of the FLASH at the specifically reserved location. If the value is $FF, then the memory has not been programmed and the program will use the ‘default’ output value for its starting point. If the FLASH has been programmed, the program will proceed with the formerly calculated output value as its starting point.

3.4.2 System Gain Algorithm

This algorithm is used to initially find the approximate operating point of the system (when a former value is not available). Essentially it supplies the power amplifier with two different bias voltages, and records the resulting change in current. The program then calculates the difference between the input current and the ideal value for the tube type. Since the input current to output voltage ratio is know, the program can immediately determine how much the output needs to change for the input current to be ideal. The main advantage here is that the algorithm does not have to spend a long time waiting for successive sampling and adjusting. It can make a calculation and find the ideal output voltage quickly in software. See Figure 3.6 for a flowchart of this algorithm. This algorithm operated well however it did not speed up the operation to a significant degree. The main problem in this algorithm is that it assumes there is a linear ratio between two specific operating points. This is only an approximation on how the non-liner power tubes will behave in other operating regions. Therefore the calculated ideal output voltage became unpredictable, and depended heavily on where the different sample calculation points were chosen. This approach was abandoned as it did not significantly decrease operation time. The former value check algorithm virtually eliminates the need for approach.

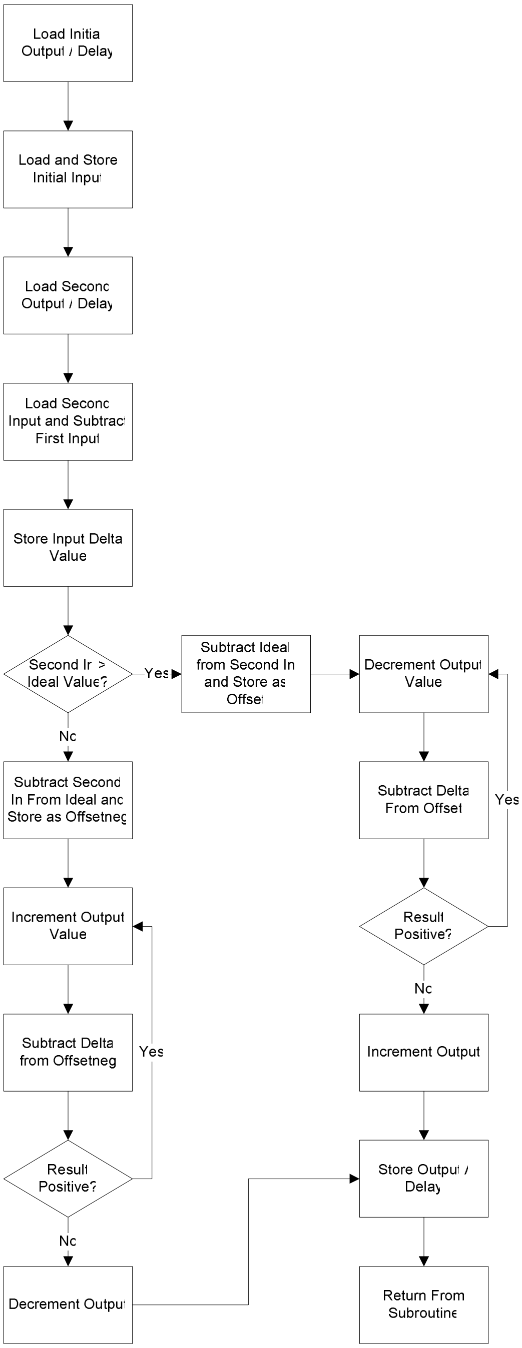


Figure 3.6: System Gain Algorithm

3.4.3 General Adjustment Algorithm

This part of the program examines the input current and compares it to the ideal value. If the input current is too high the output voltage is decremented, and vice versa. The incrementing and decrementing rates are different, so that a greater range can be analysed more quickly while maintaining precision (output value is decreased by 1, increased by 2)

3.4.4 Averaging Subroutine

Software averaging is required to get an accurate DC value from the microcontroller's ADC. Noise is essentially an AC signal on top of the sensitive sampled DC content; by sampling at several points at constant intervals and taking an average, this noise will be reduced. Ideally the best result would come from an infinite number of samples, but this is not practical. Eight samples are suitable because it can be performed in a reasonable amount of time and because division by 8 is simple by using bit shifting.

Unfortunately this particular microcontroller only supports 8-bit operations; that is the maximum value that can be represented is between 0 and 255. The microcontroller algorithm has to be designed by considering the result of the carry during these operations. This is detailed in Figure 3.7.

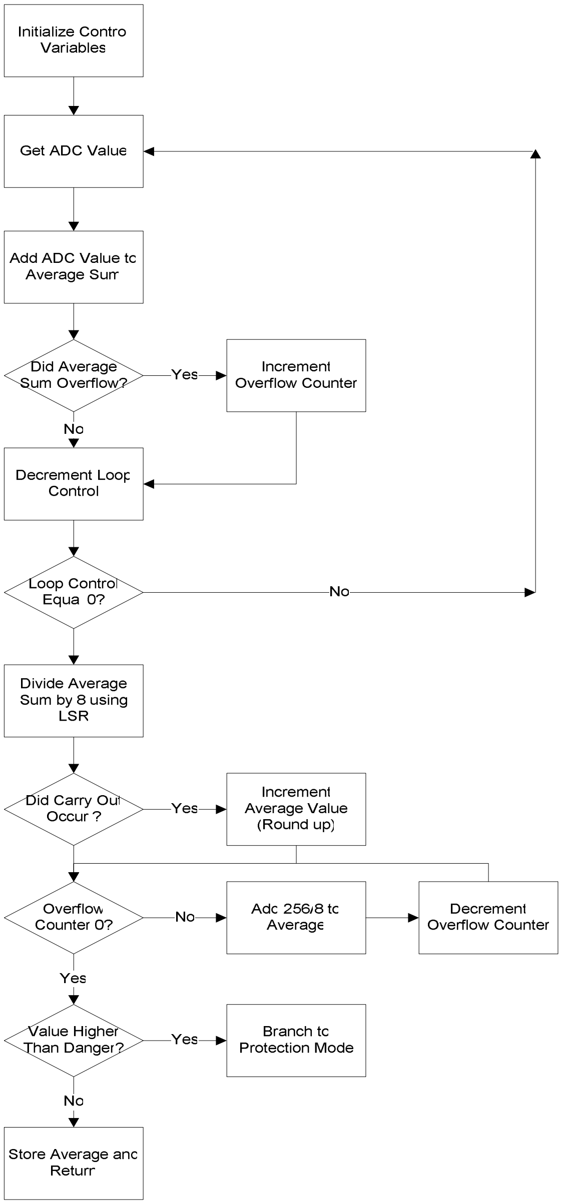


Figure 3.7: Averaging Subroutine

3.4.5 Delay Subroutine

The delay subroutine uses the internal 16-bit timer to generate an accurate time delay. The internal bus frequency of the development kit is 7MHz. By modifying the timer control register, the 7MHz frequency can be divided by 64 [10]. This makes the timer frequency 109.375 Hz, which overflows in approximately 0.599 seconds. This large delay is ideal for allowing the analog circuitry to stabilize. This delay is used in many of the algorithms presented, in most cases several times to produce longer delays.

3.4.6 Computer Operating Properly (COP or Watchdog) Subroutine

The COP circuit resets the microcontroller if the COP timer is not reset periodically by the running program [10]; a situation that only occurs if the program is not operating correctly. The COP does not work with a debugger since the debugger is generally always waiting for user input. The COP catering code has been added in the form of commented lines. When this design is brought to commercialization, those lines of code will be activated.

3.4.7 Tube Protection Subroutine

Each time the input current is measured by the algorithms, it is compared to an “excessive” value. If the input current is higher than this value, the tube is at risk of self destruction. If this occurs the program branches to a protection subroutine that attempts to shut off the tube by placing a very high negative voltage on the tube grids. If the high current is due to mechanical fault, then this solution will not help; fuses are in place to deal with these faults.

In the future this routine can also activate a warning LED to inform the user that something is wrong with the power tubes. This is a desirable feature for commercial development, though unfortunately the development kit used for prototyping reserves too many pins and the LED warning could not be implemented at this time.

Chapter 4 Testing and Performance Results

4.1 Introduction

This chapter describes the testing steps that were performed on the final prototype. The testing was done to ensure that the prototype is accurate and ready for commercialization. The prototype is shown in Figure 4.1.

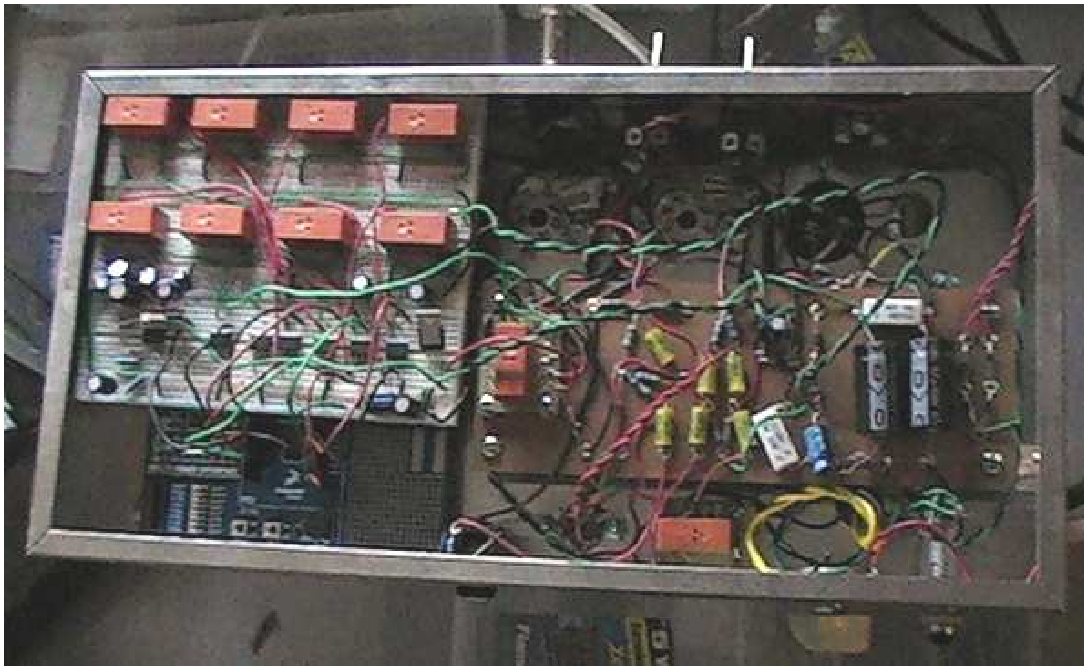


Figure 4.1: The Completed Prototype

4.2 Accuracy Test – Delay Algorithm

Since the microcontroller operates at a significantly faster speed than necessary for this circuit, it is essential to place delays in the processing loops to ensure that changes in the system have time to propagate through the system. To test the timing of the delay algorithm a simple program was written and applied to the microcontroller;

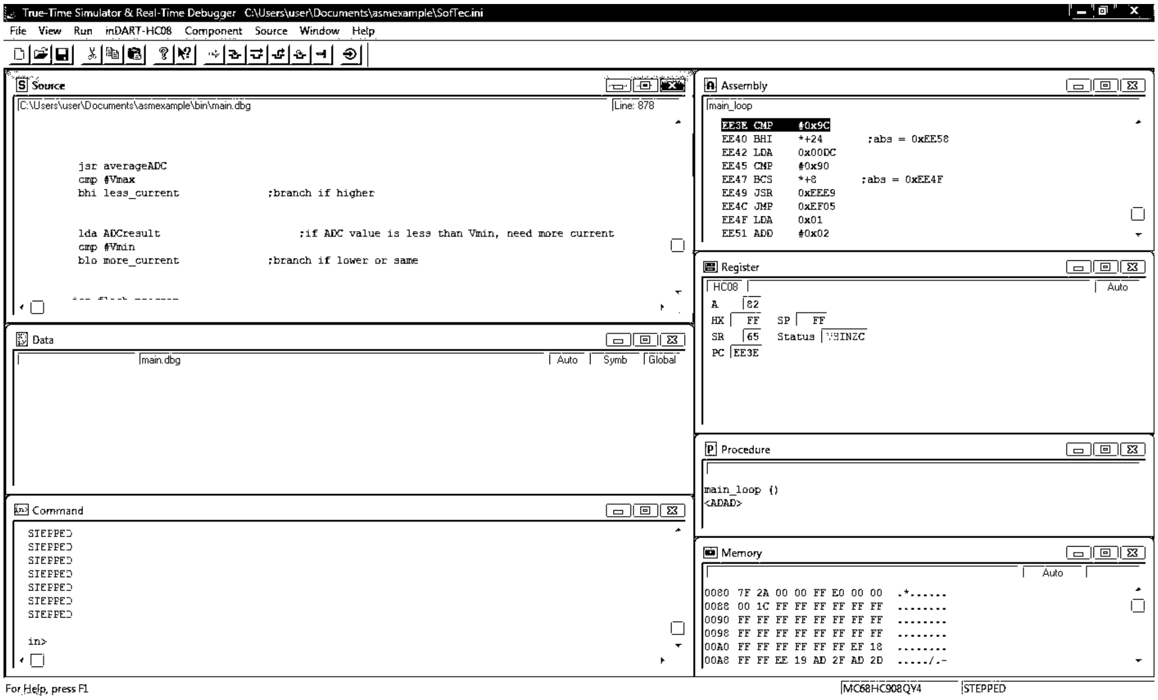
```
loop:

lda #$ff
sta ptb
```

```
jsr delay
jsr delay
lda #0
sta ptb
jsr delay
jsr delay
bra loop
```

This code alternates the output values of Port B. LEDs are connected to port B on the development board. The expected time of the delay subroutine (see main program for code) is 3.59 seconds based on the instruction delays and driving timer of the microcontroller. This code turns the LEDs on or off every 7.18 seconds. Using frame by frame analysis of a video recording of the LED, it was easy to verify that the delay of the microcontroller is running properly.

4.3 Accuracy Test – Averaging Algorithm

This test was performed to ensure that microcontroller receives an accurate DC voltage value at its input port. Each value was checked and recorded by using the microcontroller's debugger (see Figure 4.2) to step through the program.



```
        jsr averageADC
        cmp #Vmax
        bhi less_current              ;branch if higher


        lda ADCresult                        ;if ADC value is less than Vmin, need more current
        cmp #Vmin
        blo more_current              ;branch if lower or same
```

```
EE3E CMP     #0x9C
EE40 BHI     *+24        ;abs = 0xEE58
EE42 LDA     0x00DC
EE45 CMP     #0x90
EE47 BCS     *+8        ;abs = 0xEE4F
EE49 JSR     0xEEE9
EE4C JMP     0xEF05
EE4F LDA     0x01
EE51 ADD     #0x02
```

```
A    82
HX   FF   SP   FF
SR   65   Status  VHINZC
PC EE3E
```

```
main_loop ()
<ADAD>
```

```
STEPPED
STEPPED
STEPPED
STEPPED
STEPPED
STEPPED
STEPPED

in>
```

```
0080  7F 2A 00 00 FF E0 00 00  .*......
0088  00 1C FF FF FF FF FF FF  ........
0090  FF FF FF FF FF FF FF FF  ........
0098  FF FF FF FF FF FF FF FF  ........
00A0  FF FF FF FF FF FF EF 18  ........
00A8  FF FF EE 19 AD 2F AD 2D  ...../.-
```

Figure 4.2: Debugger Interface

The test was performed for several different operating points. The details from one test are examined with the following initial parameters: a 0.081 mA sampled current from the power tubes, 2.52 V at the microcontroller’s input port and 4.97 V on the microcontroller’s supply voltage. Table 4.1 shows the loops of the averaging subroutine. At the beginning of each loop a new value is presented at the input (due to signal noise).

ADC Loop #	Input Value	Accumulated Sum
1	129	129
2	131	260
3	129	389
4	132	521
5	132	653
6	126	779
7	131	910
8	128	1038

Table 4.1: Averaged Results

The algebraic average is 129.75, however the microcontroller is an integer based system resulting in a solution of 129 using an integer division by 8. Since the fractional portion is above 0.5, a roundup feature is included to increase the integer operations accuracy. Experimentally speaking, the input voltage was measured as 2.52 V approximately with a supply voltage of 4.97 V. Based on the documented operation of the microcontroller's ADC circuit, this voltage should translate to (2.52 / 4.97) x 255) 129.3. The voltmeter used to measure the input voltages reads DC values only by the use of a low-pass filter. This shows that the averaging subroutine has determined the DC value with some tolerance to the AC noise (input values were as low as 126 and as high as 132).

The process of performing this operation in the microcontroller is more difficult as it only allows 8-bit operations (values from 0 to 255). The sampling and accumulation of 8 values requires a maximum of 11 bits. The microcontroller code was written to compensate for carry's produced by addition during the division and rounding phase (See Appendix A).

4.4 Accuracy Test- Main System

Numerous accuracy tests were performed on the entire system to ensure that it was functioning correctly using five different tube sets; each set was tested three times. The system parameters are as follows: Va is 430 V, the max anode dissipation (for a pair of

EL34s) is 50 W, the ideal percent dissipation is 70%. The “Percent Dissipation” is calculated below as:

Percent Dissipation = (Cathode Current – Screen Current) x Va/(max anode dissipation)

For example: (0.093 A - 0.012 A) x 430 V / 50 W = 69.7%. Table 4.2 shows the different tubes used while Table 4.3 and Figure 4.3 summarize the result of this test; they show that the system is very accurate with several different kinds of tubes. The average percent dissipation value is 69.74%, the most deviant value is 68.8% which is 1.2% less than the ideal value of 70%.

Tube Type	Tube Test Set
JJ EL34s	1
Sevtlana EL34s	2
Electro-Harmonix EL34s	3
JJ E34Ls	4
Ruby EL34s	5

Table 4.2: Tube Types used for Testing

The tube sets collected for this test were chosen at random. The 5 different sets are from 4 different companies that are manufactured in different parts of the world. The sets were ordered from a manufacturer with no request for operating characteristic or sonic qualities. The randomness in this selection is similar to the randomness of a consumer ordering a replacement set of tubes for their amplifier, with no specificity to brand, operating parameters, or quality.

Test Number	Tube Set	Port B Output	Output Bias Voltage (V)	Cathode Current (A)	Screen Current (A)	% Dissipation (W/W)
1	1- test 1	01000000	-35.7	0.093	0.012	69.7%
2	1- test 2	01000000	-35.6	0.092	0.012	68.8%
3	1- test 3	01000000	-35.7	0.093	0.012	69.7%
4	2- test 1	00100100	-38.4	0.094	0.012	70.5%
5	2- test 2	00100100	-38.3	0.093	0.012	69.7%
6	2- test 3	00100100	-38.3	0.093	0.012	69.7%
7	3- test 1	00101000	-38.1	0.094	0.012	70.5%
8	3- test 2	00101000	-38.1	0.093	0.012	69.7%
9	3-test 3	00101000	-38.1	0.093	0.012	69.7%
10	4- test 1	00101100	-37.6	0.094	0.012	70.5%
11	4- test 2	00101100	-37.6	0.093	0.012	69.7%
12	4- test 3	00101100	-37.6	0.093	0.012	69.7%
13	5- test 1	00110100	-36.9	0.093	0.012	69.7%
14	5- test 2	00110100	-36.8	0.093	0.012	69.7%
15	5- test 3	00110100	-36.8	0.092	0.012	68.8%

Table 4.3: Tests

In this table you can see the different output values needed to achieve the same ideal power tube current value. The microcontroller determined a different binary output value for each set of tubes, which in turned produced a different output bias voltage. This is significant because it shows how the same tube type (EL34s) can require a very different bias voltage for an ideal operating point. In this case as low as -38.3V and as high as -35.6V

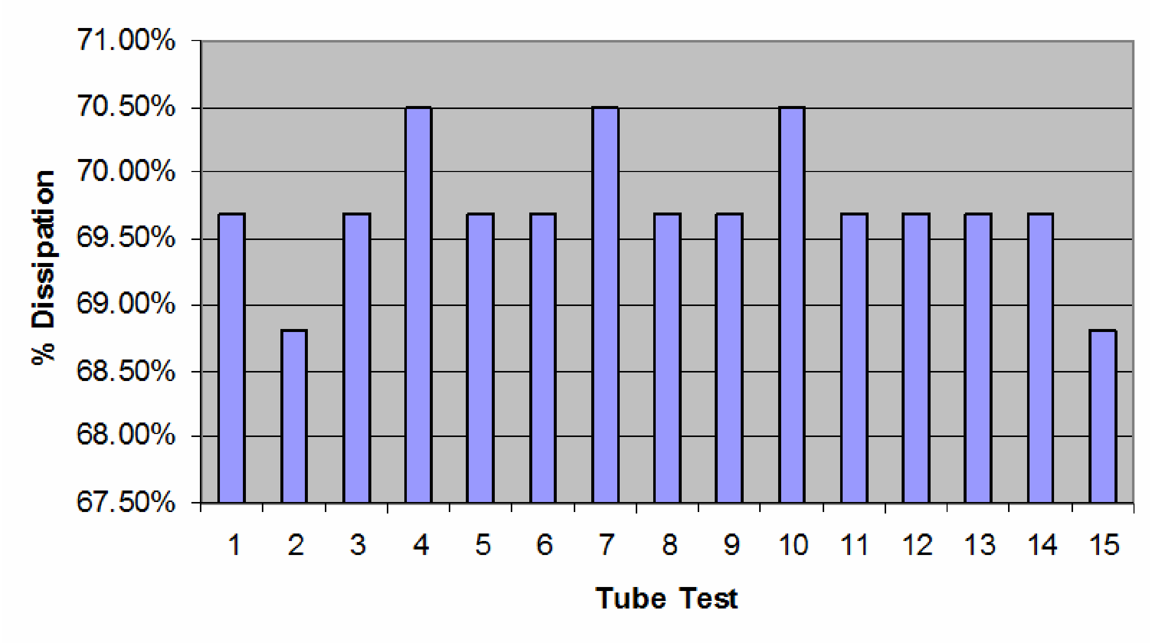


Figure 4.3: Tube Test Data

Chapter 5 Conclusions and Recommendations

5.1 Summary and Contributions

This thesis has presented a new non-intrusive digital bias control circuit for tube power amplifiers. This system automatically finds an ideal biasing point for any tube set used in the power amplifier. The control system ensures that the bias point does not change over time. The need for consumer maintenance has been eliminated; saving the consumer from potential contact with high voltage. This is a practical system that has given the sponsoring company a major competitive advantage.

This control system is superior to past designs because it uses non-intrusive sampling. This means that the control does not affect the audio signal quality in any way. This is made possible by the use of memory via a microcontroller. The microcontroller allows for other features that have not been possible in past designs, such as tube life warning and monitoring mechanisms. The final cost of the system is highly dependent on production volume, but even at low volume can be integrated into an amplifier design for less than $10 in components.

Overall the system has proven to work reliably and accurately and is ready for commercialization. It is modular, inexpensive, small, and can easily be integrated into existing amplifier designs. This system will change the way consumers use tube power amplifiers. It ensures that power amplifiers are always running at their ideal point without sacrificing any sonic qualities and eliminates the burden and danger of manual biasing.

5.2 Recommendations for Future Work

The cost and size of this design could be further reduced if a suitable digital potentiometer were available. Currently there are no digital potentiometers that can withstand a high negative voltage. As technology advances there may be a digital potentiometer that can control the high negative bias voltage for power tubes. If this happens there would be no need for multiple mechanical relays and their associated interfacing circuitry. It would also reduce the amount of static output ports needed on the microcontroller as the interface would most likely be serial.

Depending on commercial success, most of the microcontroller's interfacing circuitry could be integrated into a single IC. This would greatly reduce the cost and size of the system, though it is highly dependant on production volume. To ensure a custom IC commercially viable, tens of thousands need to be manufactured to cover the design overhead and production costs.

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Appendix A

```
; ---------------------------------------------------------------------
;       MAIN.ASM
; ---------------------------------------------------------------------


            XDEF Entry, irq_isr, main

; ---------------------------------------------------------------------
; Derivative-specific macros
; ---------------------------------------------------------------------

        Include 'MC68HC908QY4.inc'

; ---------------------------------------------------------------------
DEFAULT_ROM             SECTION

; ---------------------------------------------------------------------
; Peripheral Initialization
; ---------------------------------------------------------------------

init:



;**********************************************************************
;For commercial use, uncomment parameters for specific tube type
;*********************************************************************

;values are highly dependant on the uP supply voltage, via USB this is
;4.8V not 5V!
;example;
;Ideal cathode current = 46.5mA x2 = 93mA
;op-amp gain; 93mA x 33= 3.069
;ADC; (3.069/4.8) x 256= 160


   ;For EL34s/KT77s at 430V
```

```
   Vmax:           equ 166       ;73%

   Vmin:           equ 156       ;
   danger:         equ 200       ; dissipation too high

   ;For 6L6s at 430V
   ;Vmax:         equ 194   ; 193
   ;Videal:       equ 190   ; 190 Ideal value 49mA cathode 6mA screen
   ;Vmin:         equ 186       ; 187
   ;danger:       equ 220       ; dissipation too high




;**********************************************************************


;Output

StartvalueEL34:  equ 30  ; 30 is good start for high gain, 50 for low

;StartvalueEL342: equ %00111110 ; 62  for trans algorithm


bset 0, CONFIG1       ; Disables COP

mov #$49, CONFIG2     ; Enables external oscillator and IRQ/RST pin
mov #$02, OSCSTAT     ; Enables external clock generator

lda #0                ;sets very initial output to 0, safety measure
sta PTB

mov #$FF, DDRB         ; Configures port B as output                   mov
#$21, ADSCR        ; Enables ADC channel 1
mov #$60, ADICLK       ; Bus clock / 8     (0.875Mhz ADC clock)
mov #%00010000, DDRA   ;Makes PTA4 output for transparency
```

```
rts

; ---------------------------------------------------------------------
; Entry Point
; ---------------------------------------------------------------------



Entry:
main:

        rsp                             ; SP <- 0xFF
        cli                             ; Enables global interrupts
;       mov #$00, COPCTL ; COP write

        bsr init                        ; Peripheral initialization

        bset 4 , PTA                 ;activates transparency
        jsr delay


 ;*********************************************************************
 ;Memory check, erased bits read as 1 and programmed bits read as data
 ;*********************************************************************
      stored_output: equ $FDFA ; FLASH value from last operation

      lda #StartvalueEL34       ;default starting point
      sta PTB



      lda stored_output
      cmpa #$FF
      beq main_loop ;branch if value is FF, ie FLASH not programmed
```

```
      lda stored_output
      sta PTB

      jsr delay
      jsr delay

;**********************************************************************
;Main Algorithm
;**********************************************************************

main_loop:

      jsr delay
      jsr delay
      jsr delay



        jsr averageADC
        cmp #Vmax
        bhi less_current              ;branch if higher


        lda ADCresult        ;if ADC less than Vmin, need more current
        cmp #Vmin
        blo more_current              ;branch if lower or same


       jsr flash_program


        jmp hold                    ; Forever

more_current:

;increases PTB value which adds less resistance to output ladder, makes
;bias more positive which makes more current flow
```

```
       lda PTB
       add #2
       sta PTB                         ;stores A in port B


       jmp main_loop


 less_current:

        lda PTB
        sub #1
        sta PTB
        jsr delay


        jmp main_loop



;**********************************************************************
; Delay Suroutine, 0.599 second delay times 6 = 3.594 seconds
;**********************************************************************


delay:

        mov #%00010110, TSC

;internal bus clock/64 = 7Mhz/64= 109.375kHz,resets CLK

  delay_loop1:
        ; mov #0, $FFFF ; COP
        brclr 7,TSC ,delay_loop1

        mov #%00010110, TSC
        delay_loop1b:
        ; mov #0, $FFFF ; COP
```

```
       brclr 7,TSC ,delay_loop1b

       mov #%00010110, TSC
       delay_loop1c:
       ; mov #0, $FFFF ; COP
       brclr 7,TSC ,delay_loop1c

        mov #%00010110, TSC
       delay_loop1d:
       ; mov #0, $FFFF ; COP
       brclr 7,TSC ,delay_loop1d

       mov #%00010110, TSC
       delay_loop1e:
       ; mov #0, $FFFF ; COP
       brclr 7,TSC ,delay_loop1e

       mov #%00010110, TSC
       delay_loop1f:
       ; mov #0, $FFFF ; COP
       brclr 7,TSC ,delay_loop1f


rts


delay_short:     ; 0.599 second delay

       mov #%00010110, TSC
       delay_loop4:
       ; mov #0, $FFFF ; COP
       brclr 7,TSC ,delay_loop4


rts

;**********************************************************************
; Averaging subroutine, returns averaged value on AccA and ADCresult
```

```
;**********************************************************************

averageADC:

     ;mov #0, $FFFF ; COP

    ADCresult: equ $00DC ; global variable for ADC result

    overflow_count: equ $00D0
    lda #0
    sta overflow_count   ;starts counter at 0

    average_sum: equ $00D1
    lda #0
    sta average_sum

    loop_control: equ $00D2
    lda #7
    sta loop_control

    sum_loop:

     ; mov #0, $FFFF ; COP

     lda average_sum
     jsr delay_short ;should be short
     jsr delay_short

     ADCloop1:
     brclr 7, ADSCR ,ADCloop1       ; Waits for ADC end of conversion
     add ADR
     sta average_sum



     BCS overflow_add ;branch if carry bit set (overflow)
     bra loop_decrement
```

```
 overflow_add: ;increments overflow_count
 lda overflow_count
 add #1
 sta overflow_count

 loop_decrement:

 lda loop_control
 sub #1
 sta loop_control
 bpl sum_loop



 lda average_sum
 lsra ;divide by 8
 lsra
 lsra
 sta average_sum

BCS roundup       ;rounds up or skips straight to overflow loop
bra overflow_loop

roundup:  ; rounds number up based on lsr division carry out
lda average_sum
add #1
sta average_sum

overflow_loop:  ;256/8 = 32

    lda average_sum    ;adds 32 for each overflow count
    add #32
    sta average_sum

    lda overflow_count
    sub #1
    sta overflow_count

    bpl overflow_loop
```

```
    lda average_sum    ;compensates for initial add
    sub #32
    sta average_sum

    sta ADCresult

    cmp #danger ; if input current is too high, branch to protection
    bhi protect



    rts ;returns with average value in accumulator

;**********************************************************************
;FLASH programming, called from AUX ROM
;**********************************************************************
  flash_program:

     ;programs output value in flash

       PRGRNGE: equ $2809 ; PRGRNGE jump address
       LADDR:   equ $008A
       CPUSPD:  equ $0089
       DATA:    equ $008C


        mov PTB,DATA
        mov #$AA,DATA+1   ;place holder (needed)
        mov #$1C,CPUSPD ;fop = 7.0MHz

        ldhx #$FDFB ;Load last address to LADDR
        sthx LADDR

        ldhx #stored_output ;Load beginning address to H:X

        jsr PRGRNGE ;Call PRGRNGE routine
```

```
      lda stored_output

 rts



 ;***********************************************************
 ;Protection mode for high current
 ;***********************************************************

 protect:

    lda #0         ;turns tube off
     sta PTB

    ;***Activate some sort of warning LED or noise (commercial only)



;********************************************************************
;Holds final state
;********************************************************************


  hold:

     lda stored_output  ; for debugging
     jsr delay
     jsr delay
     jsr delay
     jsr delay

       bclr 4, PTA      ;activates transparency

      bra hold
```

```
; ----------------------------------------------------------------------
; IRQ Interrupt Handler
; ---------------------
; This subroutine is needed to implement the "Halt" debugging command.
; ----------------------------------------------------------------------

irq_isr:

        bil irq_isr                     ; Waits for the IRQ signal to go
high
        swi                             ; Jumps to monitor code
        rti

            END
```

Vita Auctoris

Carl Chute (1986 Windsor, Ontario) received his B.A.Sc. degree from the University of Western Ontario, in London, Ontario in 2008. His degree was specialized in Electrical Power Systems and he received the Hydro One Undergraduate Award.

In January 2009 he started in the Masters program at the University of Windsor. He is an active member of the Audio Engineering Society and is currently conducting research in audio electronics.