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A POWER CONTROLLER FOR
DIELECTRIC HEATING

Thesis for the Degree of M. S.
MICHIGAN STATE COLLEGE
Claire Alden Stepnitz
1950

This is to certify that the

thesis entitled

"A Power Controller for Dielectric Heating".

presented by

Claire A. Stepnitz

has been accepted towards fulfillment of the requirements for

M.S. degree in Elect. Engr.

Major professor

Date August 28, 1950

O-169

A POWER CONTROLLER
FOR DIELECTRIC HEATING

By

CLAIRE ALDEN STEPNITZ

A THESIS

Submitted to the School of Graduate Studies of Michigan

State College of Agriculture and Applied Science

in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

Department of Electrical Engineering

1950

THESIS

PREFACE

It is the purpose of this thesis to present a servo-mechanism that will control the power transmitted to a dielectric heating load. The need arises for such control when the electrical properties of materials being heated change during the process causing the complete electrical circuit to respond differently and the power flow to vary widely.

The control mechanism will be in the form of a detector and driving circuit employing vacuum tubes and a motor driven load matching element to correct errors in a prescribed amount of heating power. A control knob will be used to select the quiescent power desired.

Presentation of the material follows closely the line of thinking and experimental testing performed by the author while gathering material and building the equipment presented in the thesis. There were many electrical circuits conceived and tested but not used. These are not presented because of the numbers involved. Some were similar to the circuits actually employed and others brought only negative results with no useful information affecting the final solution.

Mathematical formulae and electrical notation will follow as closely as possible the standard form used in the Electrical Engineering department at Michigan State College. This will involve complex notation using the operator "j" as equal mathematically to $\sqrt{-1}$.

The author wishes to express his thanks to Dr. J. A. Strelzoff, of the Electrical Engineering department at Michigan State College, for suggesting the topic of the thesis and for his helpful editing and assistance in preparing the manuscript. The author also wishes to express his thanks to Professor I. B. Baccus, head of the Electrical Engineering department at Michigan State College, for putting the complete facilities of the department at his disposal for research on the project.

C. A. Stepnitz

TABLE OF CONTENTS

INTRODUCTION

Dielectric heating applications have increased many hundred-fold in the last ten years and it is difficult to foresee the limit to its uses in years to come. With the increased use of plastics, synthetics, laminated fibrous materials and many other such products in industry and the home, we can be certain that this new industrial tool will become, even more than now, a very important factor in their efficient economical production.

A complete descriptive definition of dielectric heating would be difficult. It is better to enter it in a more general field called "high frequency heating" and generalize on that topic.

For years engineers have been familiar with the phenomenon by which materials become heated due to electrical currents forced through them. At frequencies of thousands of cycles per second the heating of good conductors tends noticeably toward the outside of the mass, whereas the poor conductors are heated uniformly throughout. "Skin heating" is more noticeable at higher frequencies and in better conductors. We can put no boundary between high and low frequencies or good and poor conductors, so can only say that the uniformity of heating depends on the two factors.

There are two methods by which currents can be induced in a material. One uses a magnetic field and the other uses an electric field. We do know that both fields must exist if the intensity possesses a time rate of change. These two methods, therefore, must also overlap, depending on the permeability and permittivity of the material.

If we overlook the overlapping boundaries, we may in general define two types of high frequency heating. When the material to be heated is a good conductor, it is usually heated in a magnetic field at frequencies in a region below 1 megacycle. These can be considered as low frequencies and we may define this type of heating as "induction heating". When the material is a poor conductor, it is usually heated with an electric field at high frequencies above 5 megacycles. This is defined as "dielectric heating".

High frequency heating with all its complexities is a real science with many of its problems still unsolved. At times there are many difficulties to overcome before applying the principle to an industrial job. Inasmuch as the heating depends on the conductivity, permeability and permittivity of a material, it is necessary to consider these factors in setting up a particular job. The effect of temperature on the material is very noticeable in some cases. When certain materials are heated, the electrical properties change due to chemical or physical reactions that take place.

Fluctuations in the properties of the sample are spoken of as load transients. They affect the complete electrical circuit in the same way that disturbances introduced in any conventional linear circuit will change the operating conditions.

Load transients will usually be accompanied by a change in heating power transmitted to the sample, as the load is an integral part of the electrical circuit that produces the power.

Heating time, efficiency and the quality of the final product may be affected. In the process of molding some plastics, the heating time is very critical and load transients become a problem.

Continuous control of power to keep it at a prescribed level, regardless of transients, would be an improvement that would eliminate many detrimental effects of transients in the load.

PART I

DIELECTRIC HEATING

Heating materials, commonly classified as nonconductors or dielectrics, is accomplished by using the material as the dielectric between the plates of a condensor. The output voltage of the generator is applied directly to these plates to produce an electric field in the work. At frequencies and voltages that are ordinarily employed, there are harmonic stresses set up in the molecules of the dielectric sample that produce heat, in the same manner as in an ordinary condensor. Our arrangement is actually the same as a condensor, but at these frequencies we cannot assume the dielectric as perfect or lossless as we do in their usual treatment in circuit theory.

By using the capacitance concept, but accounting for the fact that some of the conduction current passes through the dielectric, we can approximate an equivalent circuit for plates and sample.

The current in the lines leading to the plates will deposit a charge on these plates, but some current continues through the dielectric.

Considering the rate of change of charge on the plates only,

$$\frac{dQ}{dt} = I_w - I_s,$$

where I_w is the current in the wire and I_s is the current in the sample.

With current and voltages complex functions of time, the charge will also be complex and the rate of change of Q will be jwQ.

The current between the plates will be GV, where G is the conductance and V is the voltage between plates. With this in mind,

$$jwQ = I_w - GV,$$

or

$$I_w = jwQ + GV.$$

With time varying charge on the plates, we have the same situation as in a perfect condensor and we may define:

$$C = \frac{Q}{V}$$

therefore

$$Q = CV$$

and

$$I_w = jwCV + GV = (G + jwC)V.$$

This is the well known node equation for a parallel resistor and capacitor. The approximate equivalent circuit for the heating load is this combination of resistance and reactance.

There are many factors that determine the lumped constants found above. Only when these factors are substantially constant and within limits can we accept the above results.

The physical dimensions of the circuit must be small compared with the wave length and the thickness of the dielectric must be small compared with the length and width of the plates. High frequencies bring about skin effect even in poor conductors and the linearity is no longer present.

King[1] has derived a better equivalent circuit for a parallel

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1. R. W. P. King, "Electromagnetic Engineering", 1st ed., McGraw-Hill Book Company, Inc., 1945, New York, p. 383.

plate condensor with imperfect dielectric which is shown in Figure 1. This circuit gives the impedance over a large range of frequencies. Dielectric heating applications utilize a fixed frequency so that such an equivalent circuit is not necessary here.

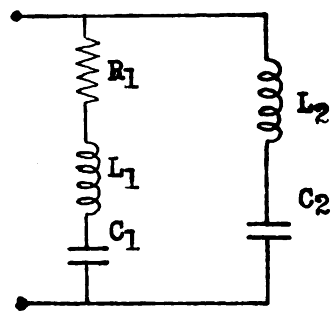

Fig. 1. Equivalent circuit for condensor with imperfect dielectric.

At a given frequency, any two terminal linear bilateral network without internal sources, can be represented by a series or parallel resistance and reactance. With materials of very low conductivity arranged as we have them, reactance would be capacitive.

We can now include the sample to be heated and the conducting plates as a lumped parameter impedance element in the overall circuit of the generator and load. There will be a flow of power that is dissapated as heat and treated as I^2R power, with a corresponding power factor due to an apparent reactive element.

This is only a satisfactory approximation as we are interested in materials which exhibit transient effects due to heating. These transients will not approach the heating frequencies so the linear assumptions are valid in a circuit treatment of the problem.

PART II

THE GENERATOR

In the high frequency heating generator used for experimentation, a Hartley oscillator circuit is employed. Fundamentally the arrangement is as shown in Figure 2.

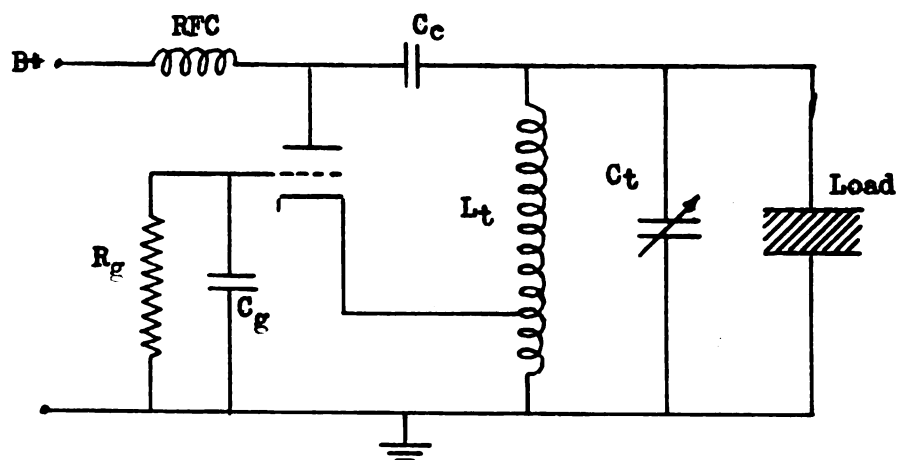

Fig. 2. Hartley Oscillator circuit used in high frequency heating generator.

The circuit operates as a Class C amplifier with regenerative feedback. The grid signal is a portion of the output voltage applied through the cathode which is connected to the tank coil. There is a self bias arrangement on the grid which makes use of grid current passing through a resistance to ground. The grid is at a bias potential due to the IR drop in this grid resistor. The ac potential of the grid is zero due to the low impedance condensor connected to ground.

The resistance between cathode and ground is negligible but the ac voltage dividing arrangement drives the cathode in phase with the plate. Consequently the grid to cathode signal is 180° out of phase with the plate and sufficient to sustain oscillations.

The Barkhausen criterion for self excitation of a single tube oscillator is

$$\beta = -\left(\frac{1}{u} + \frac{1}{g_m Z}\right),$$

where β is the ratio of feedback voltage to plate voltage and Z is the impedance presented to the plate. In the Hartley circuit, β is a real quantity. The tube constants are real quantities so Z can not have a reactive component.

The tank circuit in parallel with the load is the impedance Z. The resistance in the tank circuit can be neglected without serious error. The load is represented as a parallel resistance and capacitance so we have three reactive elements in parallel with the resistive equivalent of the load.

In order for Z to be real, the reactive elements must cancel one another and this determines the frequency. The impedance Z is therefore just the resistance of the load.

For proper operation of the generator the load impedance should be a specific value. This would restrict our heating samples to a small range of materials and sizes with the circuit as shown.

A means for realizing a constant plate load for a wide range of load impedance is provided for in a load matching network. Such a network is included in the generator but not shown in the simplified circuit of Figure 2.

The matching elements include a variable condensor and inductor in series with the load as shown in Figure 3a. By representing the load as a parallel resistance and capacitance as shown in Figure 3b, an analysis will show the operating conditions.

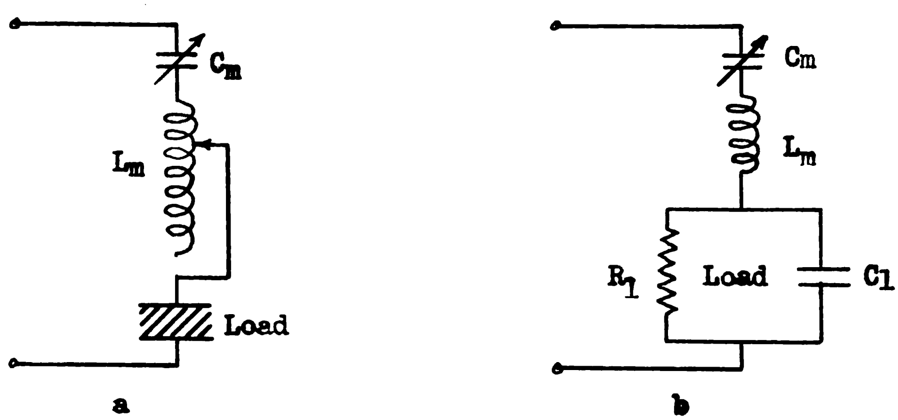

Fig. 3. Load and load matching network.

It has been shown that the overall plate load must not have a reactive term and can be represented by paralleled resistive and reactive elements. The reactive elements must cancel out and this determines the frequency. But our primary interest lies in the resistive component which determines the plate load and power flow.

We can determine this resistive component by first finding the equivalent series impedance of the load.

$$Z_1 = \frac{-jR_1 wC_1}{R_1 - jwC_1} = \frac{R_1 w^2 C_1{}^2}{R_1{}^2 + w^2 C_1{}^2} - j\,\frac{R_1{}^2 wC_1}{R_1{}^2 + w^2 C_1{}^2}$$

We may define these equivalents by

$$Z_1 = R_1' - jX_1'.$$

This impedance is in series with a pure reactive network which we can define as an impedance

$$Z_m = jX_m.$$

The total impedance of the network and load is

$$Z_t = R_1' - jX_1' + jX_m.$$

The admittance is

$$Y_t = \frac{1}{Z_t} = \frac{1}{R_1' - j(X_1' - X_m)}$$

$$= \frac{R_1'}{R_1'^2 + (X_1' - X_m)^2} + j\frac{(X_1' - X_m)}{R_1'^2 + (X_1' - X_m)^2}$$

We may define this admittance as

$$Y_t = G_t + jB_t.$$

The first term is the only one that interests us at the moment and to put it in term of resistance we can invert it to find

$$\frac{1}{G_t} = R_t = \frac{R_1'^2 + (X_1' - X_m)^2}{R_1'} .$$

With X_m adjustable over a range of positive and negative values, we see that the load impedance presented to the plate can be varied over a wide range depending on the extent of adjustment of the matching network. This is not the primary purpose of the network as we were interested in presenting a specific impedance to the plate for a wide range of load values. This is seen to be readily accomplished by adjustment of the network elements.

The equation for R_t can be simplified by using the absolute value of the total impedance.

$$|Z_t|^2 = R_1'^2 + (X_1' - X_m)^2,$$

therefore,

$$R_t = \frac{|Z_t|^2}{R_1'} .$$

It has been shown that

$$R_1' = \frac{R_1 w^2 C^2}{R_1^2 + w^2 C_1^2} = \frac{R_1 X_1^2}{|Z_1|^2}$$

and

$$X_1' = \frac{R_1^2 wC}{R_1^2 + w^2 C_1^2} = \frac{R_1^2 X_1}{R_1^2 + w^2 C_1^2} .$$

For low power factor loads that are usually found in dielectric heating, these can be approximated quite accurately by letting

$$|Z_1| = R_1,$$

then

$$R_1' = \frac{X_1^2}{R_1}$$

and

$$X_1' = X_1.$$

We can therefore find the load impedance by knowing the constants of the material and the dimensions of the sample.

From this we can find the impedance to be used in the matching network for a specific flow of power.

Nothing has been said about the frequency, voltage gradient, power density, heating time and many other factors to be taken into consideration for a particular heating application. These considerations must be determined with reference to the heating equipment and the requirements of the load.

Our purpose is not to formulate the requirements for heating, but to control the power flow after determining the amount desired.

The above analysis shows us how the load may be treated as a circuit element and how the matching network may be used.

In the equipment that was used for this work the series matching impedance was a variable condensor and inductor. The inductor had to be preset at the desired value while the equipment was off. The capacitor was connected to a power control knob on the face of the equipment. Power flow could be controlled manually using this knob.

When a dielectric possesses transient characteristics due to heating, the flow of power will not remain constant throughout the heating cycle. By altering the impedance of the matching network using the power control knob, a periodic compensation could be affected by an operator.

Almost all samples will have transients and only an investigation of the particular sample to be heated will determine whether or not such transients are detrimental.

PART III

CONTINUOUS CONTROL

Manual control offers certain advantages in many applications but can not be considered as continuous. Its limitations are in normal human inaccuracies and economic considerations. High speed assembly line techniques can be restricted in some of its phases when manual operation is used. Continuous control with closed loop systems produces much smoother performance with less error. On an assembly line it will produce better results in less time. Usually the only limitation is in the economic feasibility of a suitable design.

The problem undertaken here is to design a suitable closed loop control system that will keep the power consumed by the load at a substantially constant value. As a result the rate of heating will be kept more uniform and in most cases the heating time will be reduced.

The first consideration is in the detection of power. There are electronic wattmeter circuits used in metering power at high frequencies. At dielectric heating frequencies, such circuits must be quite critical in design to yield desireable results.

A much simpler devise which would operate satisfactorily without the difficulties involved with high frequency effects will simplify the design.

Let us investigate the problem from the standpoint of the power input to the oscillator and the losses involved.

The total power input is equal to the product of plate supply voltage and plate current. This power is dissippated in the grid circuit, the plate, the circuit elements and the load. The plate supply voltage will remain approximately constant so the plate current will be proportional to the power input.

The distribution of power can at best be approximated with a complete knowledge of the tube constants and voltages involved. We can safely say that plate dissippation and load power comprise most of the losses. Both of these will be roughly proportional to the power delivered to the circuit.

The plate current is therefore an indication, at least, of the fluctuation of power delivered to the dielectric. If this current remains constant, the output power will also be constant. This gives us a convenient tool for the detection of power fluctuations that involves direct current instead of high frequency considerations.

By introducing a series dropping resistor into the supply circuit a voltage proportional to plate current can be realized for control purposes. Figure 4 shows the fundamental rectifier circuit of the generator and the placement of the series dropping resistor R. This resistor must be small enough so there will be a negligible effect on the operation of the generator.

The supply voltage of the generator is usually set at about 2500 volts and the plate current for full load will be about 500 milliamperes. A resistor of 10 ohms was used to give a voltage of 5 volts at normal operation. This is small enough that there was no noticeable change in operating conditions.

The control voltage will be negative with respect to ground as can be seen by investigation of the current flow in the rectifier. The positive current will be from ground through the resistor and milliammeter to the plates of the rectifier tubes. The location of the connection on the left side of the meter was for convenience. There was already available an exterior connection at this point for one line of a supply voltage meter. The opposite side of the meter was connected to the bleeder at a point where a low voltage meter can be used by multiplying the face value by 100.

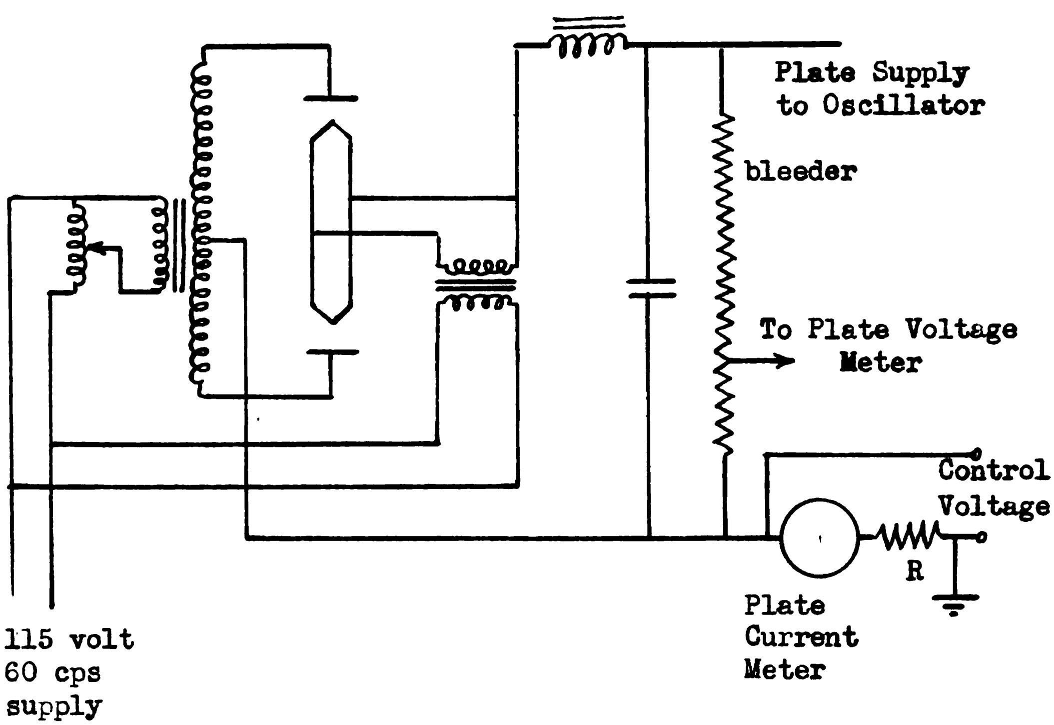

Fig. 4. Location of series dropping resistor in rectifier circuit.

Utilization of the dc control signal for error detection and subsequent control of power involves a consideration of the production of an error signal, the amplification of that signal and a control mechanism actuated by the amplified error voltage. It is necessary to decide on a suitable control mechanism as the first problem and then the circuit necessary to drive the mechanism must be designed.

It has been shown how the load matching network can be used for manual control of power. With a suitable motor driving one of the elements of this network, the same effect can be achieved with an electrical signal. The choice between a variable capacitor or inductor is obvious from many standpoints. The capacitor is easier to construct and control from the engineering standpoint; consequently, it is usually used and more readily available in a wide range of sizes.

The power control capacitor contained in the equipment was not used because of the inaccessibility of space for a driving motor and the difficulty in connecting a motor external to the equipment. This capacitor can be left in the circuit if the particular load demands it, or can be removed from the circuit with a shorting bar.

The control capacitor was mounted on the top of the equipment connected in series with the work as is the load matching network. This allows sufficient space for the servo-motor and gears necessary to increase the torque and reduce the speed.

The servo-motor is chosen for ease of control and simplification of necessary equipment. The two most widely used types of servo-motor drives for low torque applications are the two phase motor and the dc motor. The dc motor must have a motor generator set included, with the control voltage applied to the generator field. This involves three machines which becomes restricted in cost and sometimes space.

The exciting circuit for a dc drive would necessitate an electronic dc amplifier. Such amplifiers are usually unstable and in general, not as suitable as ac amplifiers.

The two phase motor will provide continuous control by exciting one winding continuously and applying the control signal to the second winding 90° out of phase. Special motors of this type are built so they will not run single phase and produce a locked torque approximately proportional to control voltage. Reversing is accomplished by applying the control signal 180° out of phase with the forward signal. These motors are constructed with a low inertia rotor so the torque to inertia ratio is higher than in ordinary ac motors. This gives a speed of response desireable with a lowering of efficiency.[2]

This type of motor was available with an operating voltage of 6 volts. The torque delivered was not quite high enough for the maximum error desired. It was decided to use the motor rather than purchase a more suitable one as it would illustrate the objective of the problem. Small 6 volt transformers were used to reduce the voltage to the necessary value.

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2. Koopman, "Operating Characteristics of 2 Phase Servo Motors", Trans. AIEE, 1949, Vol. 68, p. 319.

P A R T IV

THE CONTROL CIRCUIT

The requirements for the control circuit involve utilization of a low voltage dc signal proportional to output of the generator. A reference must be fixed to derive an error signal. The error must be amplified to drive the control motor. The output of the circuit must be ac as compared to dc input so the conversion must be included.

Figure 5 is a circuit using a 6SN7 duo-triode that will have an ac output proportional to a negative dc input. It has been shown that the input voltage would be a small negative value.

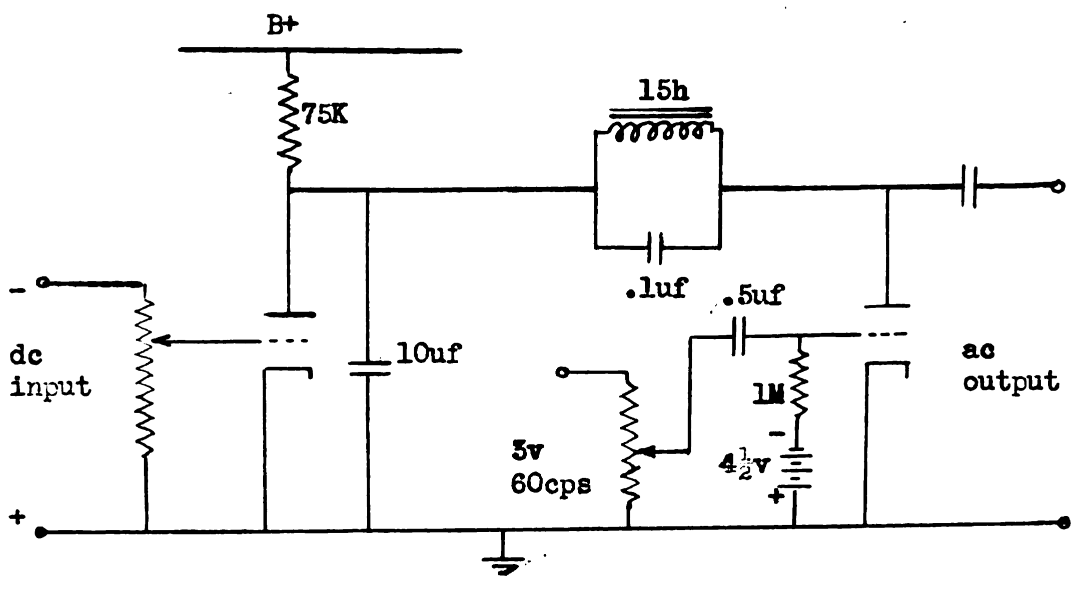

Fig. 5. Power Detector.

For analysis we will consider the first half the tube neglecting

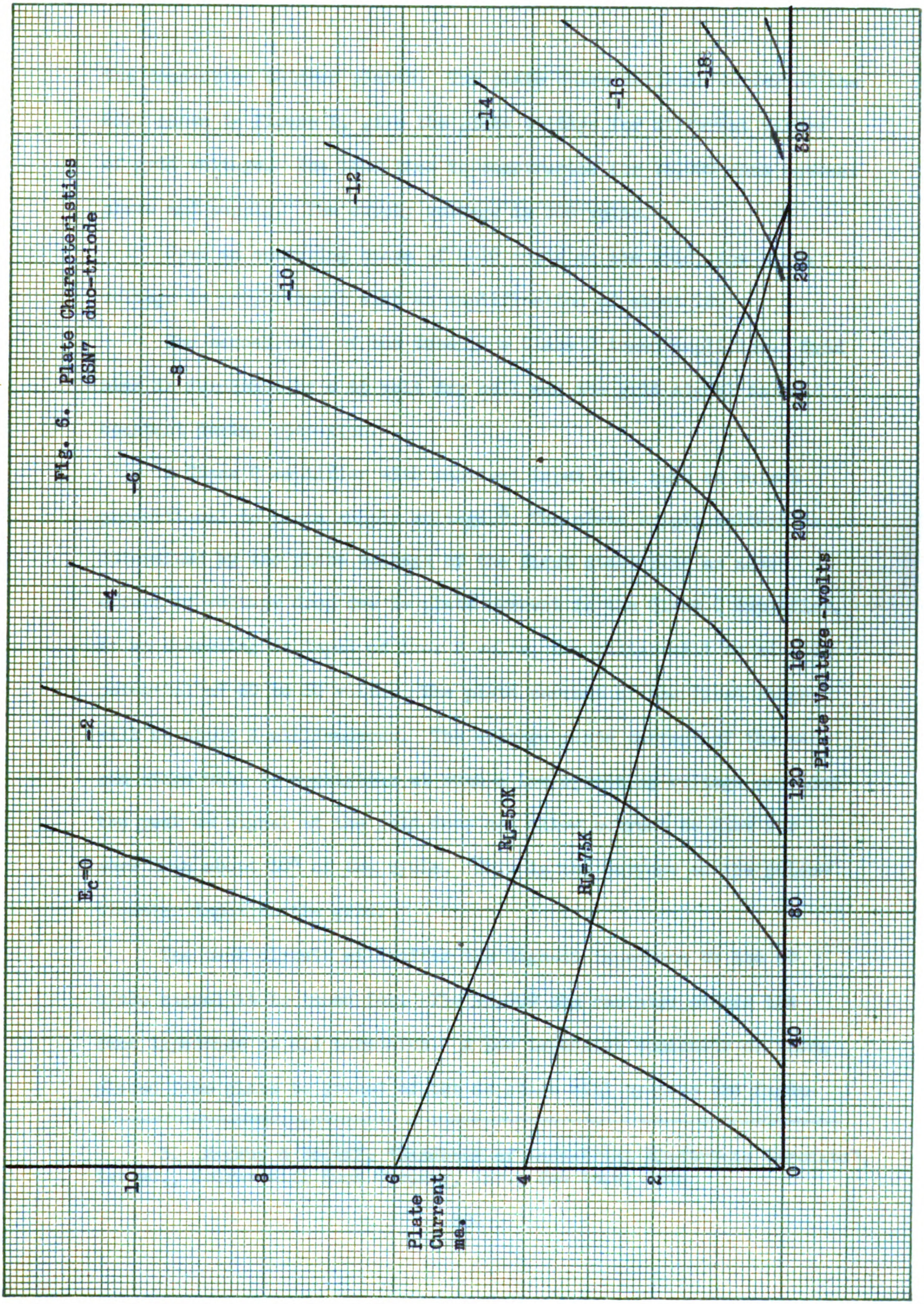

Fig. 6. Plate Characteristics 6SN7 duo-triode

the connection between plates. The plate characteristic curves of the 6SN7 shown in Figure 2, give the plate voltage for different values of grid voltage. The load line is constructed for 75,000 ohms between plate and supply. The supply voltage is 300 volts.

Over an operating range of 0-10 volts on the grid, the plate voltage is proportional with an amplification of about 16.

The second half of the tube is a Class C tuned amplifier. Grid bias is furnished by a $4\frac{1}{2}$ volt dry cell and the grid signal is held constant during operation.

A Class C amplifier with constant input will have an output proportional to plate supply voltage.[3] The plate supply voltage is determined by the plate voltage of the first stage plus an added effect of voltage drop due to plate current in the Class C amplifier. At an operating dc input of 1 or 2 volts, the plates will be at a dc potential of 60 to 80 volts. The plate current of the first stage will be about 3 milliamperes. The average plate current of the second stage will be negligible at such a low operating voltage provided the peak ac signal at the grid does not allow current to flow for more than about 30° of the cycle. This is the purpose of the potentiometer input to the grid.

The tank circuit will offer the highest impedance to the 60 cycle signal it is tuned for. The 75,000 ohm resistor offers the same impedance to all harmonics. A low impedance condensor as shown placed from plate to ground of the dc stage will by-pass the funda-

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3. Markus & Zeluff, "Handbook of Industrial Electronic Circuits", 1st ed., McGraw-Hill Book Company, Inc., New York, 1948

mental and harmonics to ground so the tank impedance is all that is effective in determining the ac output. The low impedance condensor will also cancel the effect of ripple coming on the dc signal.

The inductive element of the tank circuit is a filter choke for power supplies with an inductance of 15 henries at 75 milliammeters and a resistance of 400 ohms.

The resonant frequency of a tank circuit is[4]

$$w = \sqrt{\frac{1}{LC} - \frac{R^2}{L^2}},$$

consequently at 60 cps,

$$C = \frac{L}{w^2L^2+R^2} = .46 \text{ ufd.}$$

The inductance of a 60 cycle choke is a function of current and other variables. The condensor value is therefore only an approximation. The circuit must be tuned at the operating voltage for maximum output, best waveform and zero phase shift. The best value was found to be .1 ufd.

The output of the circuit is a low voltage 60 cycle signal proportional to the dc input. This must be compared with a reference to produce an error signal. The means for comparing two ac signals must be isolated from the two signals so that one will not alter the magnitude of the other.

Figure 7 is a circuit for producing the error voltage that will be correct in phase and magnitude.

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4. Cruft Laboratory, "Electronic Circuits and Tubes", 1st ed., McGraw-Hill Book Company, Inc., New York, 1947, p. 43.

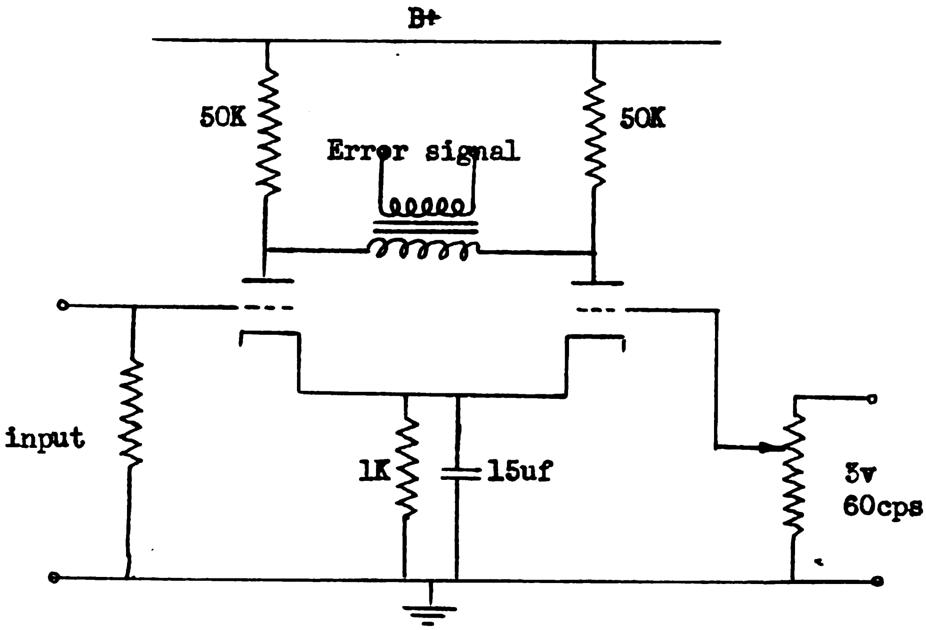

Fig. 7. Error producing circuit.

A 6SN7 duo-triode is used for this circuit also. The load line is constructed on the plate characteristic shown in Figure 6. Cathode bias fixes the quiescent operating point of each section at 6 volts bias, 3 milliamperes plate current and 155 volts on the plate. Operation will be Class A when the grid signal does not exceed 10 volts. The gain of each section will be

$$K = \frac{uR_1}{r_p+R_1} = \frac{20 \times 50,000}{8,000+50,000} = 17,$$

where the amplification factor is 20, the load resistance is 50,000 ohms and the plate resistance is 8,000 ohms.

The ac voltage across the load resistance is proportional to the input and the transformer will yield an error voltage proportional to the difference between the two grid signals. The positive error will be 180° out of phase with the negative error. This satisfies all the requirements for an error signal.

This signal is yet to be amplified to control one phase of the two phase drive motor. There are many power amplifiers that can be used for this type of application.[5] The proper choice depends upon the voltage and power requirements of the motor. Transformers are used for matching impedances and supplying the proper voltages but the vacuum tube circuit must be able to supply the driving power required.

At 6 volts, the motor to be used in this application, presents an impedance of 15 ohms at 45° and requires about 2 watts of power. This is not a large requirement for ordinary power handling tubes so a very simple circuit can be employed.

Most power amplifiers require a low impedance input which is realized with cathode followers or transformers for impedance reduction. There is also the necessity for voltage amplifiers preceding the impedance matching stages.

Beam power tubes can be used for high gain, relatively high power and high impedance input. The 6L6 is such a tube that has a maximum plate dissipation of 19 watts so a 2 watt output can be realized without difficulty. With high gain there is no need for voltage amplifying stages. A transformer must be used to match impedance between motor and tube and a parallel condensor on the primary acts to

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5. H. Lauer, R. Lesnick, & L. Matson, "Servomechanism Fundamentals", 1st ed., McGraw-Hill Book Company, Inc., New York, 1947, p. 249.

present a resistive load to the tube.

The circuit as shown in Figure 8 is the power amplifier used. Cathode bias fixes the quiescent operating point for Class A operation at bias of 20 volts, 40 milliamperes plate current and about 280 volts on the plate. The power input to the stage under these conditions will be 11 watts with a maximum output of 2 watts. The resultant plate dissipation of 9 watts is well within the maximum allowable 19 watts for a 6L6 tube.

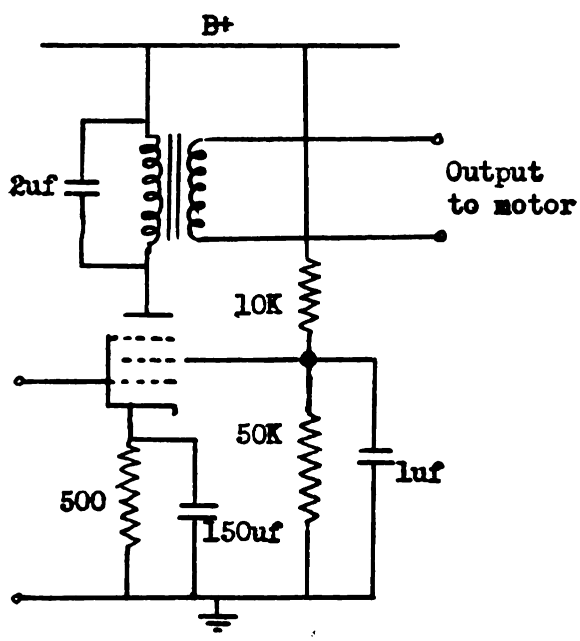


Fig. 8. Power amplifier

The power amplifier presented here was designed to meet the requirements for the motor that was used. If a motor with different ratings were desireable, it would be necessary to construct the output stage to meet the demand. Ordinarily a larger motor would be used because of higher torque and there would be a correspondingly higher power requirement.

The high frequency generator that this control was meant for had a maximum power output of 1,000 watts and did not require a large control mechanism.

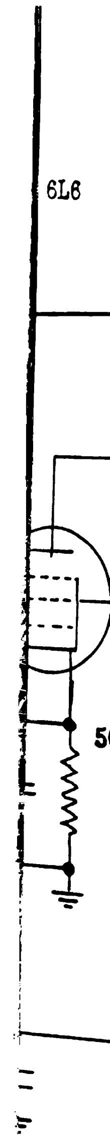
To use a circuit of this type for larger generators, it would be necessary first to determine the control capacitor size. The drive motor and speed reducing mechanism would be chosen to perform satisfactorily with that capacitor. And, as has been pointed out, the power amplifier would be designed to satisfy the requirements of the motor.

The power detector and error producing circuit will perform satisfactorily for any size of equipment. They incorporate in their simplicity a basic design for control of power in dielectric heating.

To combine the three components into a complete electronic circuit requires balancing of voltage levels, filtering of high frequency voltages, and means for performing maintenance adjustments. There should also be a setting to determine the power level that is to be kept constant. The complete circuit is shown in Figure 9.

The dc input voltage is applied to the fixed ends of a potentiometer. The input impedance is therefore a constant resistance of 50,000 ohms. This potentiometer will be the means for setting the power flow in the generator.

The complete circuit is adjusted to give no output or error signal at an input to the first grid of 1 volt. The servo mechanism will act to correct any deviation from that 1 volt input. This correction will vary the dc signal from the generator until it is at a specified



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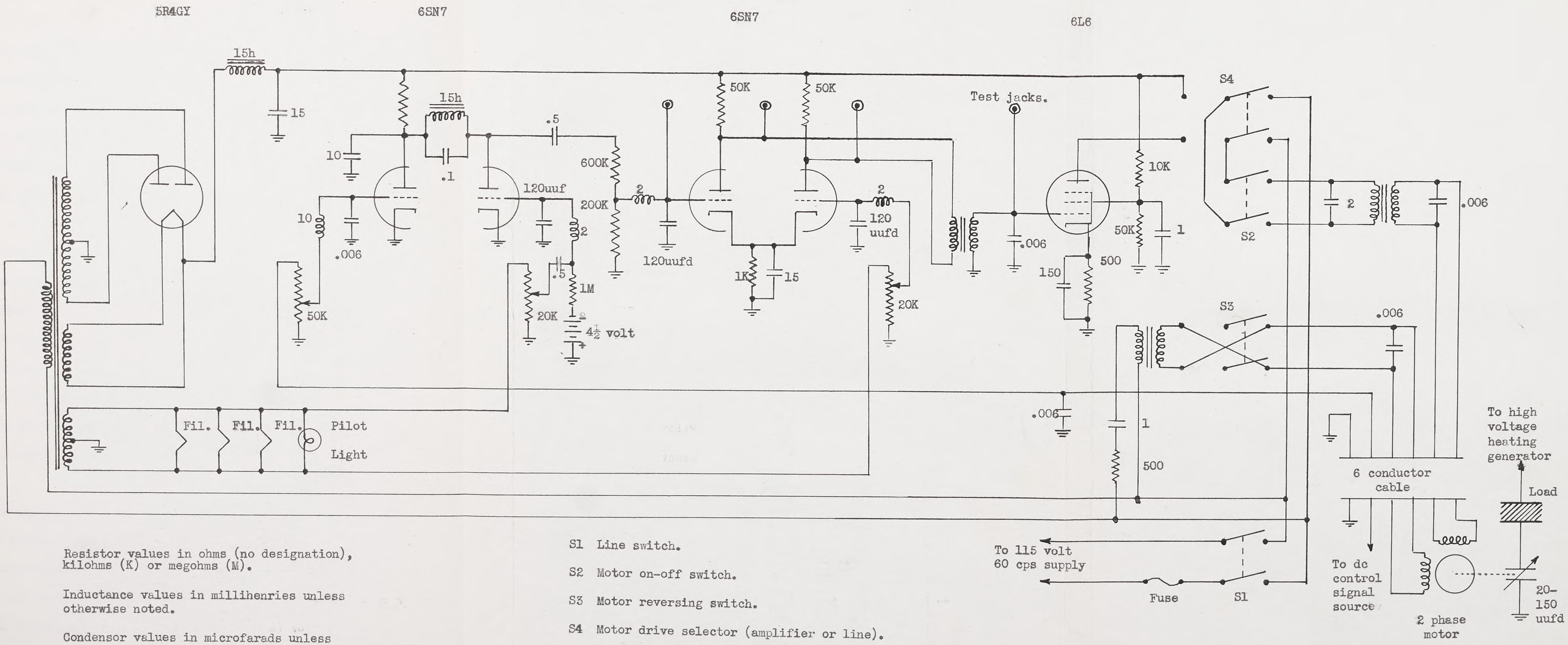

Resistor values in ohms (no designation), kilohms (K) or megohms (M).

Inductance values in millihenries unless otherwise noted.

Condensor values in microfarads unless otherwise notes.

S1 Line switch.

S2 Motor on-off switch.

S3 Motor reversing switch.

S4 Motor drive selector (amplifier or line).

Fig. 9. Circuit diagram for Power Controller.

value, determined by the potentiometer setting, to give the correct voltage at the grid.

This makes it possible to set the power at a desired level and vary it when and if the situation warrants a change. With the potentiometer set at its maximum position, such that the grid voltage will equal the input from the generator, the input will be 1 volt for zero error. Using the 10 ohm resistor in the rectifier circuit of the generator, a plate current of 100 milliamperes will supply the proper signal. At no load the plate current is 120 milliamperes in the generator that was used and 100 milliamperes is not realizeable. The above mentioned potentiometer setting is therefore, below the zero power level.

At the other extreme of the potentiometer, the grid signal will always be zero and the plate current could go beyond the limits of the generator with the circuit offering no control.

The potentiometer, therefore, can be set to realize any quiescent power requirement without the need for setting it at either extreme.

The Class C amplifier must produce a good 60 cycle wave form at the grid of the following stage. Because of the iron core inductance in the tuned plate circuit, the adjustment of the grid signal must be critical for best results. A drift in the bias supply will affect the operation considerably.

The bias supply is a $4\frac{1}{2}$ volt dry cell and the voltage will change in time. A potentiometer is used to correct for bias drift and to adjust for best output. The input to the potentiometer is supplied from one half of the center tapped filament winding in the power supply transformer. The center tap is grounded.

The output of this stage will be too high for the grid of the next stage. A resistance voltage divider is used to supply a grid signal $\frac{3}{4}$ of the output of the Class C amplifier. This signal will be 180° out of phase with the input.

The error producing circuit will produce zero error signal when the input to the two grids are equal and in phase. One signal is proportional to the dc signal from the generator. The other signal is set with a potentiometer at a constant or reference level. The source of excitation is from the other side of the filament transformer from which the Class C amplifier input was obtained. The signals are therefore in phase and adjustable for proper magnitude.

Radiation from the high frequency generator was found to have detrimental results on the operation of the circuit. This radiation was picked up in the motor windings in the cable between the motor and servo circuit and in the wiring of the circuit itself. The resulting high frequency voltages distorted all the operating characteristics of the circuit. It was necessary to provide filters to get rid of these voltages where they could not be tolerated. By-pass condensors were used at other spots.

Figure 9 shows the placement of filters on the grids of the 6SN7 tubes and by-pass condensors at the cable terminals.

It was also found necessary to connect one set of plates of the load matching condensor and the shell of the motor to ground. This minimized the high frequency pickup in the motor windings.

The circuit diagram shows the connection for four external jacks mounted on the back of the chassis. These are for alignment purposes and the author found an oscilloscope as the best means for checking adjustment. By applying one volt from a battery to the input with the power control potentiometer fully to the left, the two ac potentiometers can be adjusted for minimum distortion with maximum sensitivity.

The 1 volt input is obtained with an externally connected potentiometer and sensitivity can be tested by varying this input slightly and noticing the magnitude of the signal applied to the 6L6 grid. Testing is best accomplished with motor running at no load to approximate actual operating conditions. There is a noticeable difference with the motor turned off because of feedback effects.

Switches are provided to perform four separate functions. From left to right on the chassis, the first switch (S1) is the on-off switch for the entire control circuit. The second switch (S2) is used to open one phase of the drive motor and effectively turn off the motor. The other phase remains excited but the motor will not run single phase.

The third switch (S3) is to reverse the motor by reversing the phase of the applied voltage in the constantly excited winding. The fourth switch is to switch the motor between power amplifier and line excitation. This provides a convenient method for setting the variable capacitor with the generator turned off.

Figure 10 is the 1 kilowatt high frequency generator with the work and control mechanism mounted on top.

Figure 11 is a close up of the control mechanism. The base and movable plates of the capacitor are connected to the ground terminal of the generator. The fixed plates are connected to the bottom work plate. The top work plate is connected to the high voltage terminal of the generator.

Figure 12 and Figure 13 are the control circuit. The control switches and power control knob are seen on the front of the chassis. The cable on the rear is a six conductor cable to bring in the dc signal from the generator and to drive the servo-motor.

Fig. 10. High Frequency Generator

Fig. 11. Control Mechanism and Motor

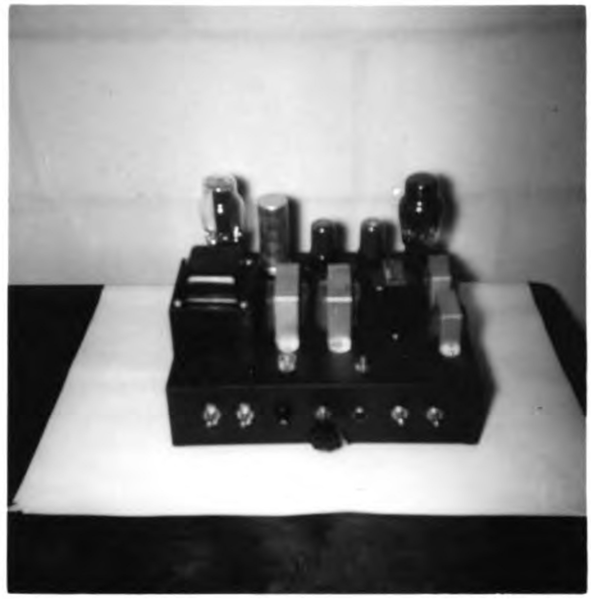

Fig. 12. Control Circuit

Fig. 13. Control Circuit Wiring

PART V

EXPERIMENT RESULTS

We could chose any number of representative loads for testing the controller. A true test must be performed on a sample that would present transient properties when heated. Because of the difference in dielectric constants and conductivity between wet and dry materials, it was thought that a drying process would yield the desired transients.

Damp drift wood was chosen because it was easily obtained and was economically suited for experimental purposes. Because transients was the only requisite, the usefulness of the product was not considered.

The aim is to keep the heating power in the load at a constant value. There was no method available for measuring this power but it has been pointed out that plate current is an indication at least of power and fluctuations of power. We can even approximate the power by reading the difference between no load and full load plate current and multiplying it by the plate supply voltage.

The circuit was tested by heating a piece of drift wood with no control and noting the plate current drift as a function of time.

A comparable piece of wood was heated and the plate current recorded again. Figure 14 is a plot of the results. The smooth curve shows how the current, or power, drifted downward as the sample became dry. The sawtooth curve shows the results when the controller

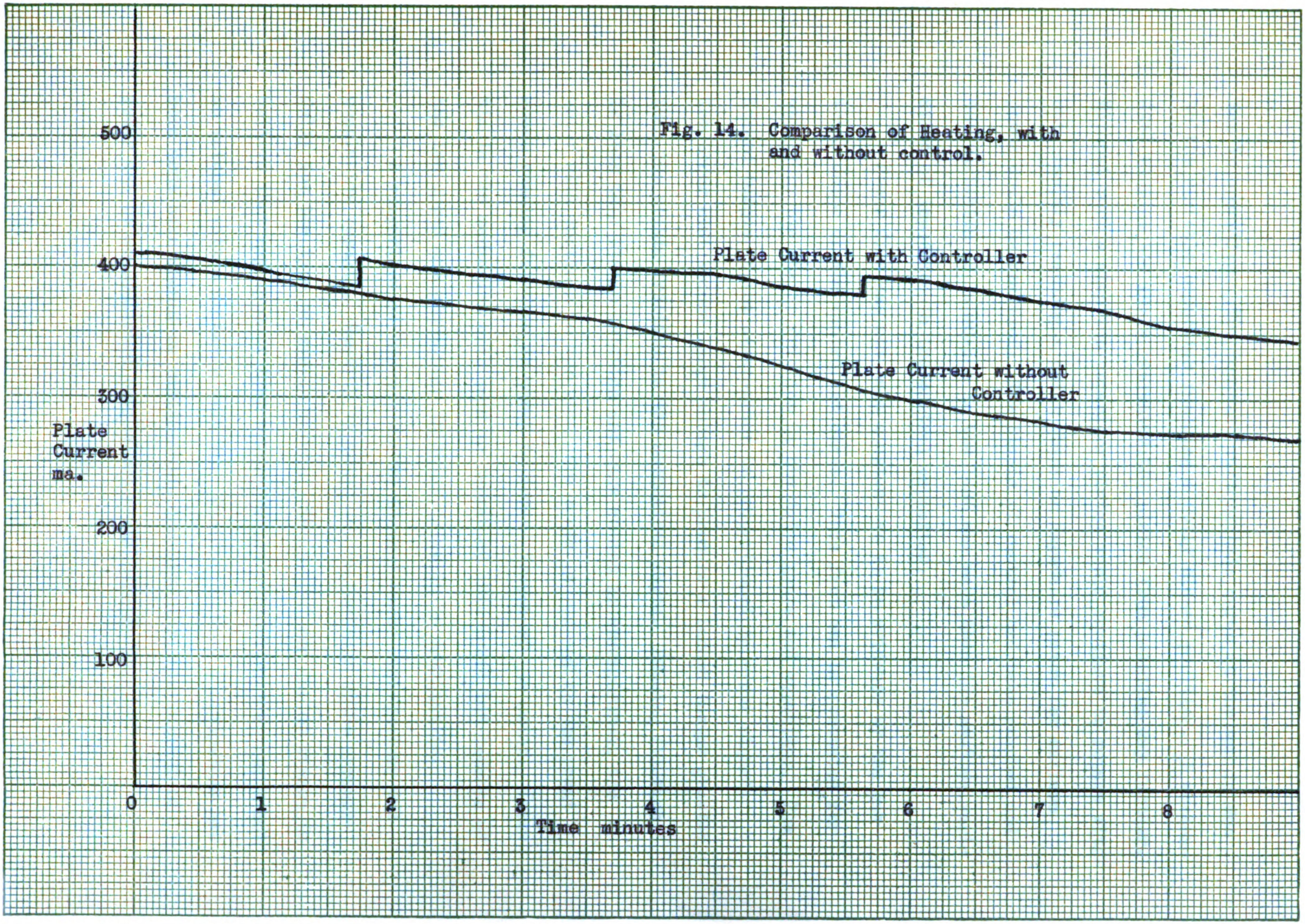

Fig. 14. Comparison of Heating, with and without control.

was in operation. The downward rift of this curve at the end is due to the variable capacitor reaching a fully closed position. A mechanical stop on the gears prevented the plates from rotating any further. Without such a stop the capacitor plates would continue to rotate without possibly reaching a point where an impedance match for maximum power could be realized. The limits of control had been reached and the variation of impedance in the load was more than the maximum variation of impedance in the control capacitor.

Power flow was not held constant as is in evidence by the saw-tooth shape of the controlled curve. This fact can be accounted for mainly by the static friction in the drive gears and capacitor. The locked torque of the servo-motor is proportional to error signal. The error must become large enough to produce a locked torque greater than the static friction in the mechanical parts. Running friction is less than static friction and once motion is accomplished, the motor will continue to run until the error is reduced to the point where running friction is equal to locked torque of the motor. Inertia in the mechanism will tend to overshoot this point but because of the low speed and non-linear friction there is no oscillation.

A comparison of the two curves clearly shows satisfactory and conclusive results. Control of power can be realized quite successfully for the type of sample tested. The author can see no reason to believe that any type of load would exhibit properties that could not be matched with a suitable network. Control of such a network as has been done here should be realizeable; consequently, the control of power can be accomplished continuously and automatically.

A servo-mechanism has been built that would keep power substantially constant. Should there be a desire for control varying with time, a slightly more complex circuit with controlled reference voltage could easily be built. This would be a study beyond the scope of this thesis.

Further investigation would probably lead to improvements on the circuit presented. Better mechanical construction and a more suitable drive motor would certainly yield a smoother response.

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