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DESIGN AND PERFORMANCE OF A NO-SINGLE-FAILURE CONTROL SYSTEM FOR THE MINI-BRAYTON POWER CONVERSION SYSTEM

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16. Abstract

A breadboard control system was developed for the 0.5- to 2.0-kWe (Mini-Brayton) Nuclear Power Conversion System. The control system consists of the ac-dc conversion, voltage regulation, speed regulation through parasitic load control, and overload control. A no-single-failure configuration was developed to attain the required reliability for a 10-year design life of unattended operation. The design principles, complete schematics, and performance are reported. Testing was performed on an alternator simulator pending construction of the actual Mini-Brayton alternator.

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SUMMARY

The Mini-Brayton Power Conversion System is a radioisotope-fueled dynamic system being developed for spacecraft application and is a closed-loop Brayton Cycle System designed for the 0.5- to 2.0-kWe power range.

The control system described in this report was designed and developed to investigate the feasibility of a high-reliability efficient electrical control system. The 10-year unattended design life requires extensive redundancy, yet the low power rating of the system dictates a small, highly efficient electrical system. A breadboard of a control system, incorporating these requirements, was developed and tested on an alternator simulator since an actual Mini-Brayton alternator was not available for testing. The design concept and tested performance of the control system are reported, with complete schematics of the control system and a description of the alternator simulator.

The control system converts the alternator output to filtered, regulated dc power; and controls the turbine alternator speed by parasitic loading. The goal of a no-single-failure design was met, with a power loss of as little as 3 percent of the system power output, and with voltage and speed regulation of better than 1.0 percent.

INTRODUCTION

The Mini-Brayton power conversion system is a dynamic system using a radioisotope heat source. It is sometimes called the Isotope Brayton Power System. The power conversion system uses an inert gas in a closed-loop Brayton cycle. The major components are the heat source, radiator, recuperator, turbine-alternator-compressor assembly, and the electrical system. The turbine-alternator-compressor assembly is a single-shaft, gas-bearing, four-pole modified Lundell, or Rice, alternator operating at 52 000 rpm. The Mini-Brayton system is described in reference 1.

The Lewis Research Center has been involved in dynamic power conversion systems since 1960. Previously, a 2- to 10-kWe Brayton cycle system was developed. The Mini-Brayton program is an extension of this technology for the 0.5- to 2.0-kWe power range, and is the first dc system. Dynamic power systems are capable of high efficiency (25 to 30 percent), light weight (projected 0.14 kg/W or 0.3 lb/W), and long life. These characteristics have been demonstrated in the 2- to 10-kWe system (ref. 2).

The electrical system consists of two parts. One part is a variable-frequency inverter used to motor the alternator to start the system. The other part is the electrical control system, which provides rectification and filtering of the alternator output, voltage regulation, speed control, overload protection, and startup control. This report is concerned with the fundamentals of operation and performance of a breadboard electrical control system operating on an electronic alternator simulator.

The control system is a small part of the power system, but the control system will have a major effect on the total system performance. The desired characteristics were not well defined, so this control system was developed to determine what performance is reasonable, and to develop necessary technology. Although a complete design is shown, it is intended as a base, and many variations are possible to adapt to different missions.

The design concept and performance of the control system are presented in this report. Appendix A contains complete schematics and detailed descriptions of the circuits developed. The electronic alternator-simulator on which the testing was performed is described in appendix B.

DESIGN PHILOSOPHY

In the design of the control systems, the following performance philosophy was adopted:

(1) High reliability
(2) Minimum complexity
(3) Lower power loss
(4) Light weight
(5) Low cost

The objectives are highly interactive and are listed in the order of importance. Reliability is of prime importance and is attained by various techniques, primarily through extensive redundancy. The control system is designed with a "no-single-failure" concept. Any single component in this system can fail without seriously degrading the performance of the Mini-Brayton power system. This concept is in direct confrontation with the other four design goals, but yields approximately an order of magnitude improvement in the mean time to failure calculations. Another reliability improvement technique used is component derating, in voltage, current, power, temperature, gain, and safe operating area considerations. Reliability is further improved by minimizing the use of matched, high precision, or adjustable components.

Complexity is minimized by the extensive use of integrated circuits, and functional integration, wherein, for example, a speed sensor is used for speed control, overload protection, and startup. Also, a minimum of different component types is used, and a circuit may be used in several places, which would ease conversion to hybrid circuits for significant size and weight improvement.

There are two important considerations relating to low power loss. The first is reduction of available output power. But also, any power loss must be radiated to space from a low temperature ($\approx 25^{\circ}$ C) radiator, which affects the system weight. This second consideration is particularly important when considering the design of the speed control, which will be discussed later.

Low power loss is attained primarily through the use of low power integrated circuits and high efficiency switching stages, where practical. Also, high impedance circuits and Darlington-connected power stages are used extensively, with careful design employed to minimize the increased noise sensitivity.

Weight is primarily a function of power loss and mechanical design. In the breadboard system, weight was not considered. And even in a flight design the weight is almost completely out of the control of the electrical designer aside from power loss considerations.

Cost of the electrical system is a small fraction of the total system cost. However, the considerations discussed under complexity would effect a considerable reduction in the electrical system cost.

ELECTRICAL SYSTEM DESCRIPTION

The electrical system, shown in figure 1, performs the following functions:

(1) Alternator output rectification
(2) DC output voltage filtering
(3) Output voltage regulation
(4) Overload control
(5) Speed control
(6) System startup control

Alternator

The alternator is a four-pole, three-phase Rice alternator operating at a nominal 52 000 rpm. A Rice alternator (ref. 3) is a brushless solid rotor machine. The output is nominally 66 volts rms L-N, 1733 hertz, Y-connected. The design power rating is 2.17 kWe into a rectifier load, having an effective power factor of 0.82.

Rectification

The alternator output is rectified with a three-phase, full-wave bridge rectifier. The alternator neutral is floating. The unfiltered dc output is nominally 120 volts dc, with a 6-volt rms ripple at 10.4 kilohertz, six times the alternator frequency.

The alternator could have been wound as a six-phase star, and six-phase half-wave rectifier used, with only one diode in series with the output and, therefore, higher efficiency. But the peak inverse diode voltage would have been higher, and net power losses in the alternator windings would have been greater, due to the higher rms to average current in the windings, even with an interphase transformer, offsetting the reduced diode loss. Because the constant diode drop (0.7 V each) is a greater fraction of the output voltage in a 28-volt dc system, the six-phase star would probably be the preferred connection in a 28-volt dc system. But for the 120-volt dc system the increased diode stresses outweighed the slight efficiency gain possible.

Output Filtering

Filtering (fig. 2) is required to reduce the voltage ripple at the dc output bus. Additionally, the switching of the parasitic load resistor (PLR) generates considerable noise, which must be attenuated, on the dc bus. A small capacitor (C_1 in fig. 2) is connected across the rectifier output which reduces high voltage noise spikes generated by the rectifier commutation, reducing the peak inverse rectifier voltage. An L-C (L_1-C_3) section is used to attenuate the output ripple before the dc output. A second L-C section attenuates the noise generated by the PLR switching. Because both L-C sections are effectively in series to isolate the PLR noise from the dc output, this filter arrangement is much smaller than if the PLR was connected, through a filter, directly to the dc output bus.

This and following circuits are discussed nonredundantly. The redundancy concepts are in a following section.

Output Voltage Regulation

Voltage regulation is accomplished through alternator field current control. The alternator has four identical fields, which are paralleled as shunt fields. As the alternator sees a constant load (user load plus PLR), a series field is not needed for fast regulation during load transients. The voltage regulator (VR) can fully excite the alternator with only two fields; therefore, reliability is improved with the redundant shunt fields. Field excitation is supplied from one of three sources (fig. 3(a)). During normal operation, voltage attained from the alternator neutral is used. The three-phase full-wave rectifier on the alternator output appears as a three-phase half-wave rectifier referred to the neutral. Figure 3(b) shows a conventional three-phase half-wave rectifier. This is the connection used in the control system, except that the rectifier output is connected to ground, and the output is taken from the neutral tap. Peak rectification results in an 80-volt dc source.

During startup, a 28-volt battery supplies the power for field flashing and the control circuits. For short circuits or severe overloads, excitation is supplied from the 28-volt battery or current transformers in the alternator output. In this latter mode, the shunt field and current transformer combination functions almost identically with a series field arrangement. The current transformers always supply some of the field power, but do not provide full excitation during normal operation.

Field current is controlled with a pulse-width-modulated (PWM) transistor switch. The error signal controlling the pulse width is derived by comparing the output voltage, through a resistive divider to a zener-controlled reference voltage. The difference is amplified through a proportional-integral-derivative loop to attain accurate steady-state regulation with good transient response and stability.

As the turbine supplies nearly constant torque to the alternator, an overload will reduce the speed of the alternator. If the overload is not removed or reduced, the speed will continue to decrease, even for a few percent overload, until the machine stalls. To control overloads and the resultant speed reduction, a modified volts-per-hertz (V/Hz) regulation is used to reduce the output voltage as the speed drops, effectively reducing the load (ref. 4). Stable operation, at reduced output voltage and speed, is then attained during overloads. V/Hz regulation is effected by reducing the reference voltage, and regulated output voltage, approximately 5 percent per percent of speed reduction. If the V/Hz regulation cannot effectively shed the load, at 10 percent underspeed the overload cutoff circuit turns the regulator off completely. With no field current the alternator output goes to zero, effectively removing the overload, and the machine accelerates. At 92 percent speed the voltage regulator turns back on at reduced voltage. The machine will slow down again if the overload persists, cycling until the overload is removed. An external 28-volt source is required to power the logic during overload cutoff.

Short circuit protection must be provided externally to the control system. A short circuit unloads the alternator (high current but low voltage and therefore low power), which causes the machine to accelerate. The fault must be cleared before the machine overspeeds. When the system is used as an approximately 1-kWe system or less, the alternator losses will be great enough that the system will not overspeed, but the fault must be cleared to prevent overtemperature in the alternator.

Alternator Speed Control

Speed control is required to prevent destruction of the machine through overspeed and to maintain the 52 000-rpm design speed, optimized for the power output and efficiency. Additionally, large speed variations would cause a small torque impulse (1.2×10^{-4}(m)(kg)(sec^2)/percent or 0.1 (in.)(lb)(sec^2)/percent) to be transmitted to the spacecraft structure.

Alternator speed is determined with magnetic pickups sensing transit of each compressor blade. Alternator frequency has been used in the past (ref. 5) to determine speed but gives no indication during motor starting, short circuit output, or periods of no field excitation. Magnetic pickup frequency is also higher than the alternator frequency (10.4 kHz against 1.73 kHz at design speed), allowing faster transient response.

The magnetic pulse output is a frequency proportional to speed. A transistor switched capacitive charge pump is used as a frequency to voltage (F/V) converter. The F/V converter output is amplified about a set point to provide a control signal proportional to frequency in the 90 to 110 percent speed range. This signal is pulse-width-modulated and controls a transistor switch, modulating the voltage across the parasitic load.

Additionally, since the Mini-Brayton operates with a constant input power, the total load, user plus parasitic, must be constant to maintain constant speed. If the parasitic load was changed, independent of speed, but inversely with changes in user load, then constant load would be attained without requiring a speed change to affect a parasitic load change. If the output voltage remains constant, user load power can be determined by measuring only the user load current. In the control system a user load current shunt is used, and shunt voltage is subtracted from the speed sensor signal. This provides predictive or load compensation and determines the proper parasitic load within a few percent. The speed sensing control loop then provides only small corrections, yielding high overall accuracy without high feedback loop (speed sensing) gain. Thus, the stability and transient response considerations of high gain proportional or integral controllers are avoided.

Auxiliary Circuits

Alternator control during startup requires no additional circuitry. Below 90 percent speed the overload cutoff circuit inhibits the voltage regulator and the parasitic load is off below 95 percent speed.

The carrier signal for pulse width modulation is generated by a 5.2-kilohertz square wave oscillator. The triangle wave necessary for modulation is formed separately in each modulator by integrating the square wave.

A 15-volt dc power supply is required for low level circuits. It is obtained from the 80-volt field supply through linear series regulators. A complete schematic of the circuits is included in appendix A.

No-Single-Failure Configuration

To attain a high reliability over a 10-year unattended operating period, extensive redundancy had to be used. Except for the motor starting equipment and the alternator, any single component may fail without significantly affecting the operation. Additionally, some alternator failures, such as an open field, are tolerable, and no single failure in the motor start inverter will affect the Mini-Brayton system once it is started. Since restarting once in flight is not required, the motor start system has a very short useful life and complete redundancy was not required.

Failures are defined as follows:

(1) A failure is generally any failure of a part, including opens, shorts, or parameter changes. However,

(a) Resistors only fail by a change of value or an open, no shorts.

(b) Inductors do not fail shorted.

(2) Wiring shorts are not considered.

(3) Overload is a fault (i.e., a single failure and an overload may cause abnormal operation).

Each of the functions in figure 1 except the alternator and motor start inverter is made redundant. Typically this is done by means of several techniques.

In the case of a block whose output is an analog signal, a best-of-three approach is used. Essentially three identical circuits are connected in parallel, and external feedback loop is used such that the output is equal to the median signal. Thus, any single failure will not affect the output.

Another arrangement is the "quad switch," used in the switching stages. In this configuration, four circuits are connected in a series-parallel arrangement. If any element opens or shorts, there is still a series or parallel branch which maintains the correct switching function.

Some circuits, such as the V/Hz circuits, the overload cutoff and the user load sensing are three independent parallel channels. Failure of one of these channels may cause a slight change in performance, as discussed later.

The redundancy configurations are shown in appendix A.

PERFORMANCE

Test Results

The breadboard control system (fig. 4) was tested on a simulation of a turbine-alternator, using essentially a specialized analog computer driving a power amplifier. A discussion of the simulator is presented in appendix B.

The control system was tested to determine the voltage regulation, including transients, output ripple, power consumption, and speed control. Short circuit characteristics are discussed, but the alternator simulator is not capable of working into a short circuit, so no testing was done.

All performance testing was performed at 25° C ambient. However, subcircuit tests were conducted over a -55° to $+125^{\circ}$ C range, with no performance degradation and minimal changes in the regulation of voltage or speed.

Voltage Regulation

Figure 5 shows the steady-state output voltage regulation. Figure 5(a) plots output voltage against gross alternator output with no user load. The Mini-Brayton system is designed for 0.4- to 2.0-kWe gross power. In the less than 200-watt range the output filter impedance begins to appear primarily capacitive instead of inductive, and peak instead of average rectifies the alternator output, which would require a large reduction in field current. The output voltage, therefore, rises slightly (0.1 percent) at light load. Conversely, above 2.0-kWe the field current has to increase rapidly as the machine saturates, causing a 0.2 percent reduction in output voltage at 2.4 kWe.

Figure 5(b) illustrates the effect of user load to parasitic load balance on the output voltage. As shown in the figure, there is essentially no effect on output voltage until the user load exceeds the available output power. The gross alternate output was 2.0 kWe, and overload occurred at approximately 1.9 kWe. The additional 90 watts was consumed in control system loss (60 W) and field power (30 W). Steady-state voltage regulation from both input power and user load variation is better than ±0.2 percent from 0.1- to 2.4-kWe gross power and 0 to 100 percent available user load.

Figure 6 shows the overload characteristics. Output voltage is plotted against applied load. The actual output power is limited to approximately 400 watts, the gross alternator output, so the voltage decreases as the load impedance is reduced. The V/Hz regulation controls the output voltage during overload operation.

Transient characteristics of the output voltage are shown in figures 7 and 8. Figure 7 is an envelope of the maximum voltage excursions and recovery time for load switching transients. User load was switched from 10 to 85 percent and 85 to 10 percent available power. A typical transient response is shown in figure 8. The worst case of transient response which could be caused occurred when switching from full load to no load at maximum (2.0-kWe) gross alternator output. The overshoot was 23 volts, decaying in 25 milliseconds.

Ripple voltage on the dc output was approximately 2 volts rms, maximum, the main component being the 5.2-kilohertz PLR switching frequency.

Speed Control

Steady-state speed regulation is shown in figure 9 for the three gross power levels of 0.4, 1.2, and 2.0 kWe. As the gross power level varies, the alternator speed (frequency) varies approximately 50 Hz/kW, or ±3 percent. However, the Mini-Brayton is designed to work at constant gross power and due to the user load compensation circuit the speed variation with user load is approximately 0.1 percent/kW, or 2 Hz/kW, in the 10 to 85 percent load region. Approaching 0 or 100 percent parasitic load, the speed control becomes slightly nonlinear, causing a greater rate of speed change with load, as seen in figure 9. The alternator speed (frequency) is also shown during overload when the volts-per-hertz (V/Hz) function regulates the speed and output voltage. The speed increase in part of this region is due to the effects of the user load compensation.

The transient behavior is shown in figure 10 for 10 to 85 percent load change at 2-kW gross power operating condition. The acceleration of the rotating unit is approximately 2 Hz/sec (6 rad/sec^2) resulting in a peak torque of 2×10^{-5} (m)(kg) or 0.017 (in.)(lb) and a torque impulse of approximately 12×10^{-6} (m)(kg)(sec^2)/kW or 0.01 (in.)(lb)(sec^2)/kW.

The speed variation with gross power will be a very slow change which will occur only during startup and with isotope decay. A digital crystal-controlled speed sensor (ref. 6) has been developed which reduces the steady-state error to crystal accuracy (<1 ppm/yr) but has no effect on transient behavior.

Power Loss

There are two considerations in the power consumption of the control system. One is the minimum power loss, which is the loss at zero parasitic load, and indicates the maximum dc output power which can be obtained for a given gross alternator output. The power loss for a 2- and 0.4-kWe system are given in table I.

The second consideration of power consumption is the maximum power dissipated in the control system which must be conducted to a cold plate or directly radiated. The power in the PLR is radiated directly, and because of the high operating temperature

($\approx 900^{\circ}$ K or 1200° F), does not require a large radiator. In addition to the minimum power loss indicated for a 2-kWe system, 60 watts, at full PLR, the PLR drivers dissipate approximately 30 watts, and the control power increases by 10 watts. Therefore, approximately 100 watts must be removed from the control system package.

Reliability

Fault testing was not generally performed on a piece-by-piece basis but on a functional level. The basic functional blocks were shown in figure 1. For example, a component failure in the VR preamp will generally cause the output to go to either plus supply voltage or ground. By forcing a voltage regulator preamplifier (VR preamp) output to plus supply and ground, the effect of nearly all failures in the preamp can be determined. Switching devices were tested by simulating a short or open circuit at the output of the device. The effects of these faults are given in table II.

Other components, such as rectifiers, filter capacitors, and current transformers will typically affect the output ripple, but nothing else.

In general, normal operation, except speed regulation, is unaffected by a single failure. Overload operation, which is already considered a fault, is affected - but the system operates in a safe mode. Typically, faults could occur in several separate areas (i.e., one in a PLR drive and one in a VR preamp) and still not affect operation. However, because of the speed sensor-VR preamp-power-supply interactions, and so forth, two isolated failures could cause a system failure. The system reliability was computed to be on the order of 0.99 for 10 years based on exponential failure rates for flight components. This is approximately an order of magnitude lower failure rate than would have been attained nonredundantly.

CONCLUSIONS

The control system breadboard was developed to evaluate various control concepts which differed from previous systems. The primary developmental goals were in the areas of high reliability through redundancy, minimizing power loss, accurate speed control, and the use of integrated circuit designs. The major performance parameters and their effects are as follows:

1. Voltage regulation was approximately ±0.2 percent for power input and load variations. An overload circuit reduces the output voltage during overload.

2. Speed regulation is 2 hertz per kilowatt for load changes, restraining the maximum torque to a spacecraft to approximately 2×10^{-5} (m)(kg) or 0.17 (in.)(lb).

3. Control system loss varies from 4 percent of gross power at a 0.4-kWe level to 3 percent at a 2-kWe power level.

4. Calculated electrical system reliability is 0.99 for 10 years. Single component failures have a minimal effect on the system performance.

Lewis Research Center,

National Aeronautics and Space Administration,

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506-23.

APPENDIX A

COMPLETE SCHEMATIC AND CIRCUIT DETAIL

The complete schematics of the control system are shown in figure 11; component values are shown on the drawings. Some of the significant features of the design are discussed in the rest of this appendix.

Analog Circuit Redundancy

The VR preamp and speed sensor produce analog signal outputs. Three identical independent circuits are used for each, and the outputs are combined to give a net output which is equal to the median signal. The configuration is shown in figure 12.

The output will be the average of the three amplifier outputs. If it is assumed that input $A > B > C$, then input A is greater than the desired output, so amplifier A will put out approximately 15 volts, the supply voltage. Similarly, amplifier C will put out zero volts. But amplifier B will operate linearly with its output, B', between 0 and 15 volts such that the net output, fed back to its inverting input, is equal to input B. The useful output range of this circuit is approximately 5 to 10 volts, one-third to two-thirds supply voltage. Outside this normal 5- to 10-volt operating range the output will equal either the highest or lowest signal, depending on whether the output is below or above the normal range, respectively.

Further detail on this connection is available in reference 7.

Voltage Regulator Frequency Response

The voltage regulator should operate at a high dc gain to attain good voltage regulation but with a large phase margin to achieve transient stability. The calculated Bode plot of the voltage regulator and field transfer function is shown in figure 13, and a simplified VR preamp schematic is shown in figure 14.

The dc gain, controlled by R_1, R_2, and R_3 is high to give adequate steady-state regulation. Gain rolloff is started by C_1 and R_3, well below the field time constant. Then C_1 and R_4 generate a lead component to compensate the field time constant and maintain a 90° phase margin. After the loop gain is less than one, C_2 and R_3 form a high frequency rolloff. Other time constants of the loop are also above the gain-equals-one frequency.

Parasitic Loading

The parasitic load is divided into three sections. Each is sized for 50 percent of the system power so any pair can fully load the system.

Two sections are driven at equal powers, but 180° out of phase. Thus, even with a 5.2-kilohertz switching rate, which lowers switching losses, the ripple is at 10.4 kilohertz. At a higher speed the third PLR section is switched in, also operating at 5.2 kilohertz.

Each PLR section is controlled by two series-connected transistor switches. A short in any switch has no effect, while an open merely transfers the load to the third section. Failure of a section reduces the circuit gain, accounting for the loss of speed regulation in table II.

APPENDIX B

ALTERNATOR SIMULATOR

The Mini-Brayton turbine alternator was not available for testing during this phase of the development program. In order to get dynamic testing on the electrical control system, an electronic simulation of the turbine alternator was developed. The simulator provides a real-time full power three-phase output closely simulating the predicted alternator performance. A block diagram is shown in figure 15.

In a Brayton turbine-alternator system, alternator speed (near design speed) is very nearly the integral of the difference between turbine input power and gross alternator output power, with an integration constant defined by the turbine torque and the rotating unit inertia. In the simulator turbine power is a potentiometer setting, and output power is measured with a three-phase wattmeter. The integrator constants simulate the torque-inertia response of the rotating unit. The output voltage of the integrator controls two voltage to frequency (V-F) converters, one simulating alternator frequency, and one for the magnetic pickup output required for the speed sensors. A phase-locked-loop maintains the 6.5-to-1 ratio required between these signals.

The alternator field is simulated by a passive inductor-resistor (L-R) combination. The voltage applied to the field is conditioned to provide the proper time constant and fed through a nonlinear network to simulate the alternator saturation. Comparison of the predicted field transfer function and the simulation is shown in figure 16.

The conditioned field signal is multiplied with the V-F output to form a signal proportional in amplitude and frequency to the required alternator output. The signal is converted to a three-phase signal, and amplified in a three-phase power amplifier. A passive L-R impedance is connected to the power amplifier output to simulate the armature impedance.

A schematic of the simulator is shown in figure 17. The alternator frequency V-F, three-phase converter, the power amplifier, the output impedance simulation, and the passive L-R field simulation are not shown.

The simulator does not accurately account for the following: (1) a less than rated voltage field transfer function, (2) field saturation above 2.2 kWe, (3) the effect of alternator speed on the field function, (4) alternator power loss, (5) the decreasing power available from the turbine as speed decreases, and (6) gas loop flow variations. However, the inaccuracies should have only a negligible effect on the results obtained since the testing involves small variations in nominal speed and voltage.

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TABLE I. - CONTROL SYSTEM POWER LOSS

[Zero parasitic load.]

Power analysis	2-kWe system	0.4-kWe system
Gross input power, kWe	2	0.4
Rectifier loss, W	50	10
Voltage regulator loss, W	5	3
Speed control loss, W	.3	.3
Power supply loss, W	2.5	2
Miscellaneous loss, W	2.5	2
Total loss, W	60.3	17.3
Total loss, percent of input power	3	4
Field power consumption, W	30	13
Available output power, W	1910	365

TABLE II. - SINGLE POINT FUNCTIONAL LEVEL FAILURE ANALYSIS

Failure	Effect
VR preamp	Overload cutoff speed[a], V/Hz regulation[b] changes
Field driver	No effect
Speed sensor	Overload cutoff speed changes[a]; speed control deteriorates to ±1/2 percent for load changes
PLR driver (fail-shorted)	No effect
PLR driver (fail-open)	Speed control deteriorates to ±2 percent for load changes, ±5 percent for power level changes
Overload cutoff	Overload cutoff speed[a], V/Hz regulation[b] changes
User load sensor	Speed control deteriorates to ±2 percent for load change
Carrier generator	No effect
15-V dc power supply	Combination of all effects as supply failure affects circuit redundancy

[a]Change is due to possible change of median signal in redundant speed sensor channels (see appendix A); change would typically be less than 1 percent.

[b]V/Hz regulation will only reduce output voltage ≈10 percent before overload cutoff removes load.

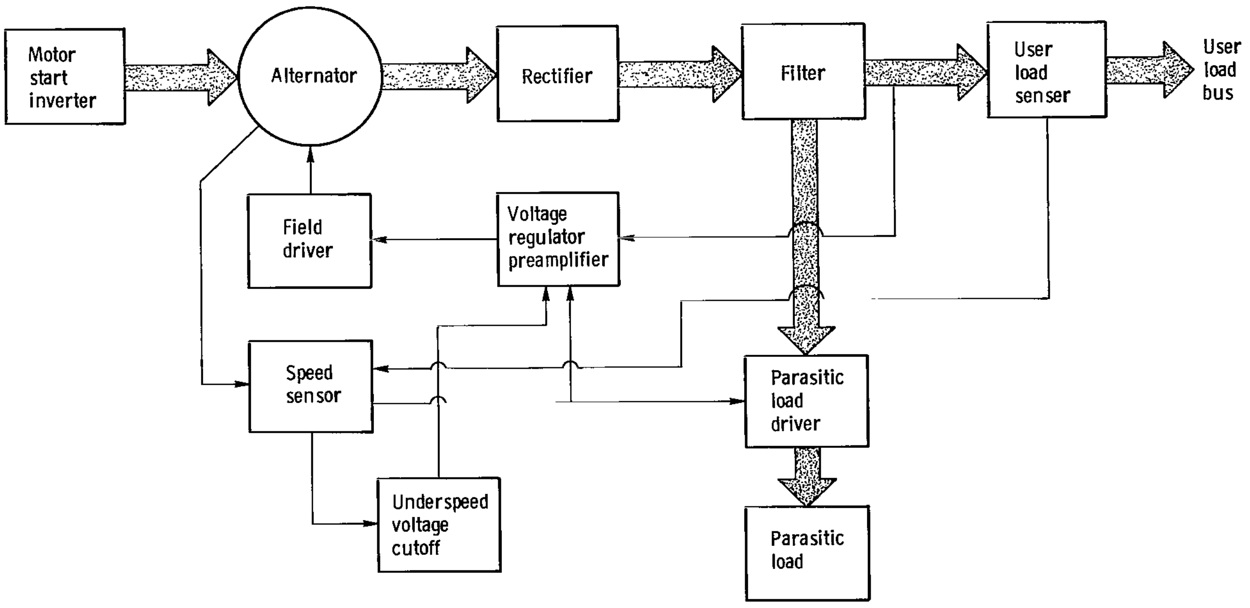


Figure 1. - Mini-Brayton electrical system.

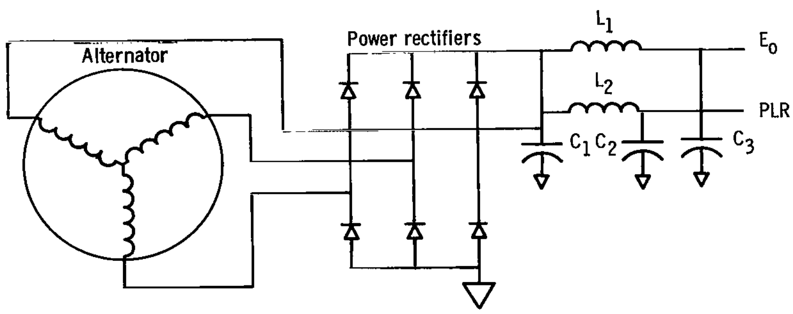
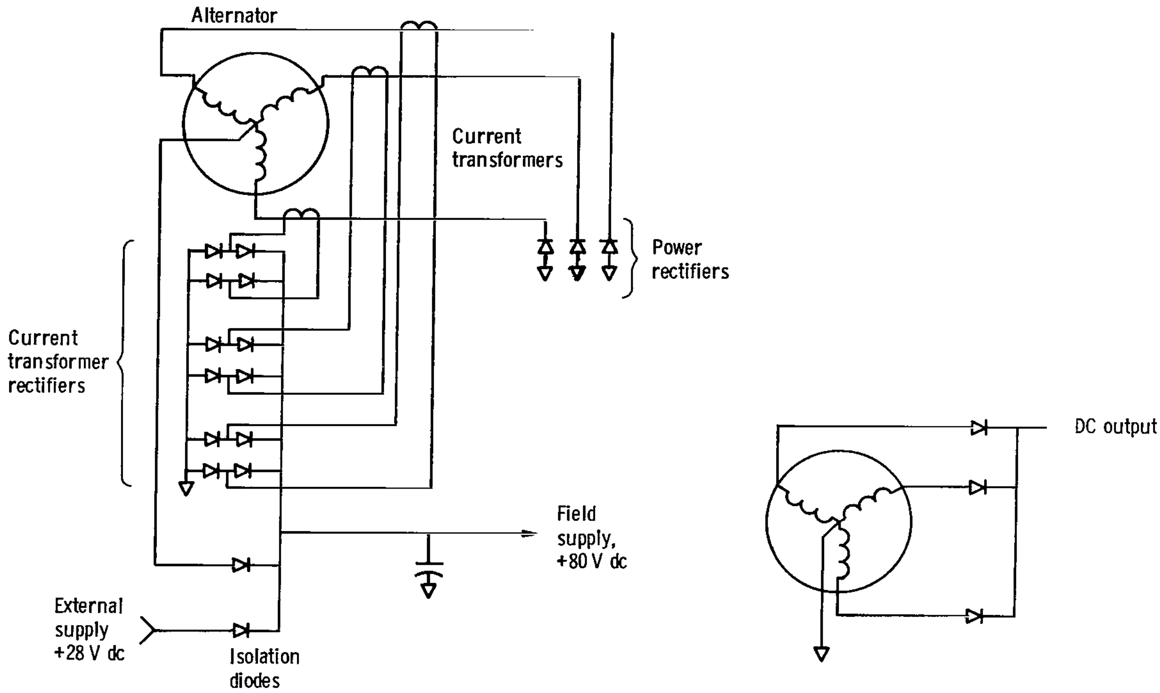


Figure 2. - Rectifier - filter configuration.



(a) Complete circuit.

(b) Equivalent three-phase half-wave rectifier.

Figure 3. - Field excitation supply.

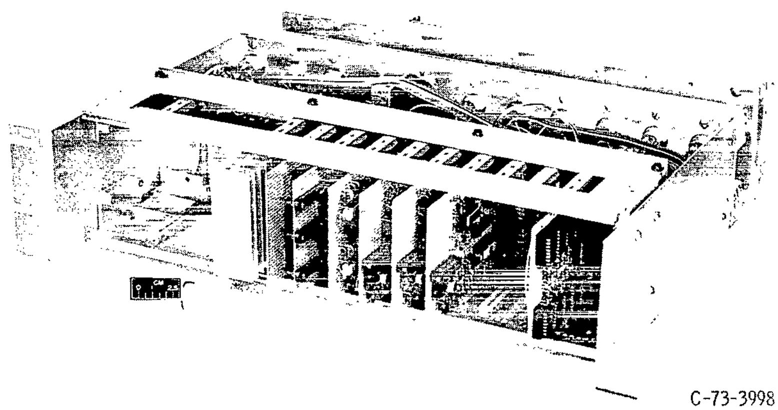


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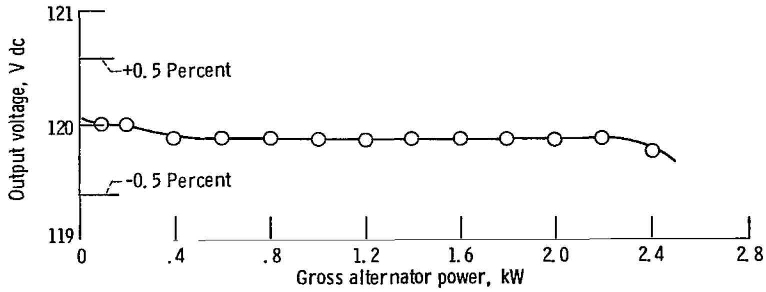
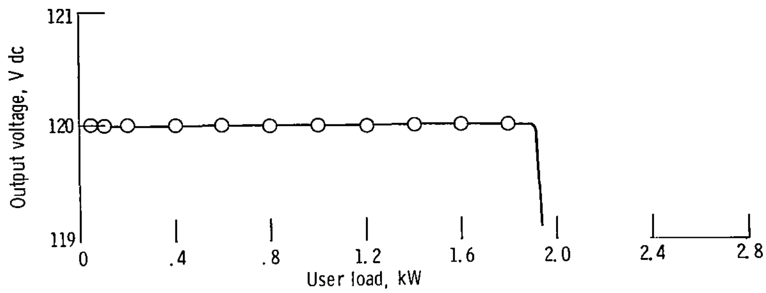
Figure 4. - Mini-Brayton electrical control system breadboard.



(a) Regulation as a function of gross alternator power. User load, 0.



(b) Regulation as a function of user load. Gross alternator power constant at 2 kWe.

Figure 5. - Output voltage regulation.

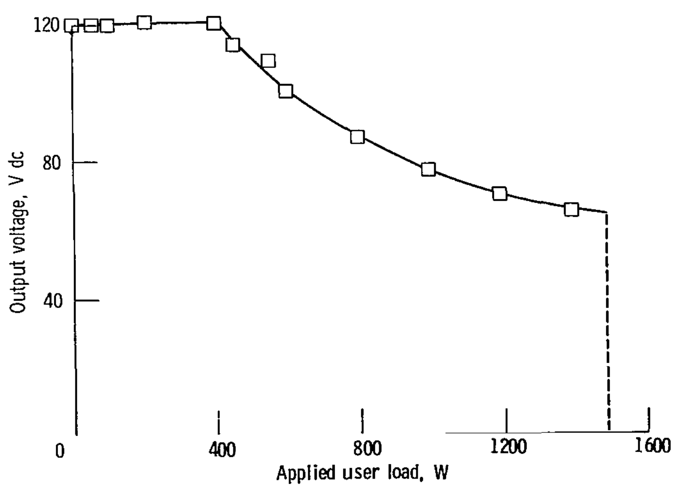


Figure 6. - Overload characteristics. Gross alternator power, 0.4 kWe.

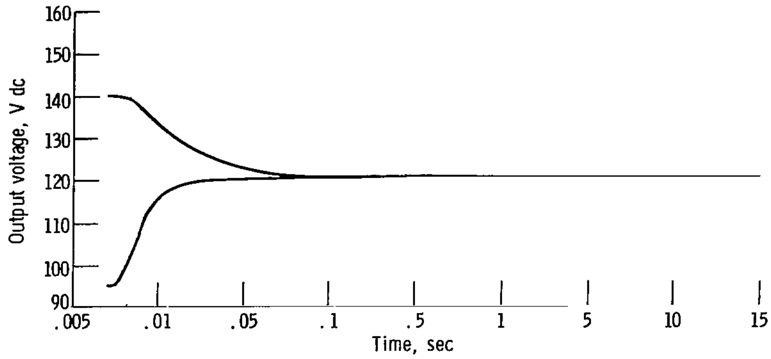


Figure 7. - Envelope of transient responses. Load switching, 10 to 85 percent, 85 to 10 percent.

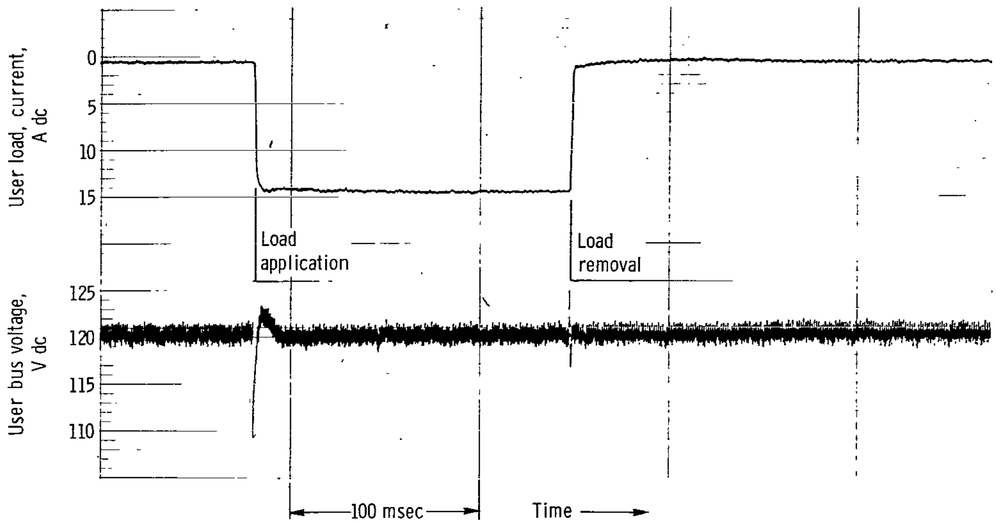


Figure 8. - Bus voltage transient response. Load switching, 10 to 85 percent; gross alternator output, 2 kWe.

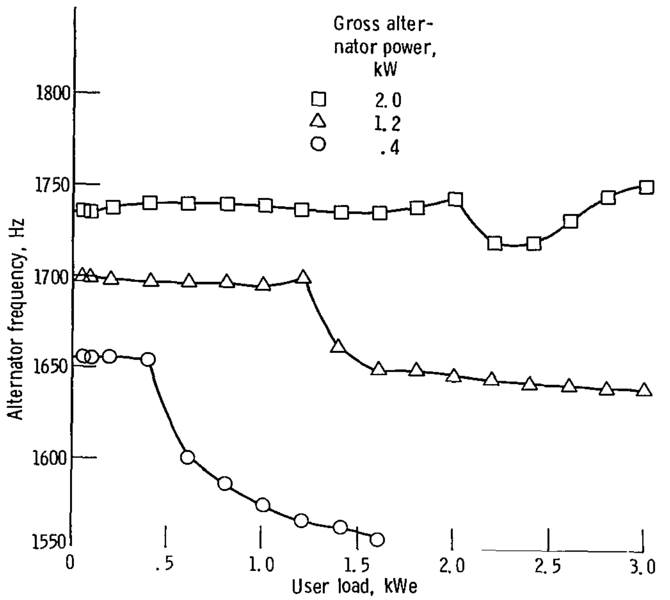


Figure 9. - Speed control characteristics.

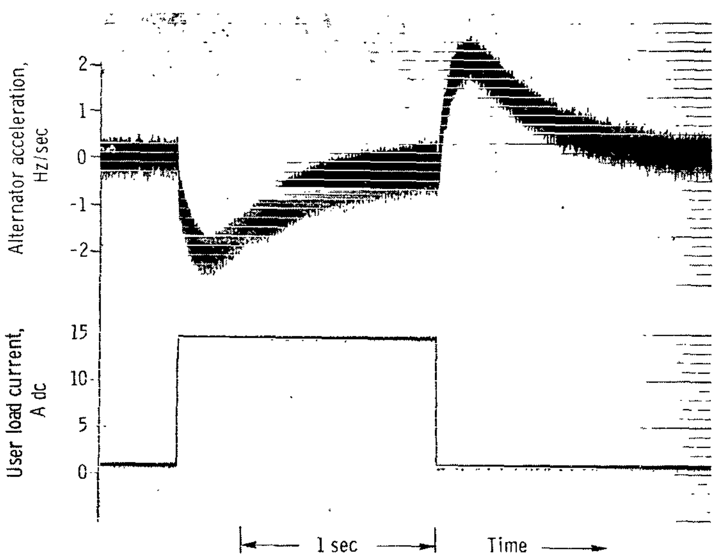
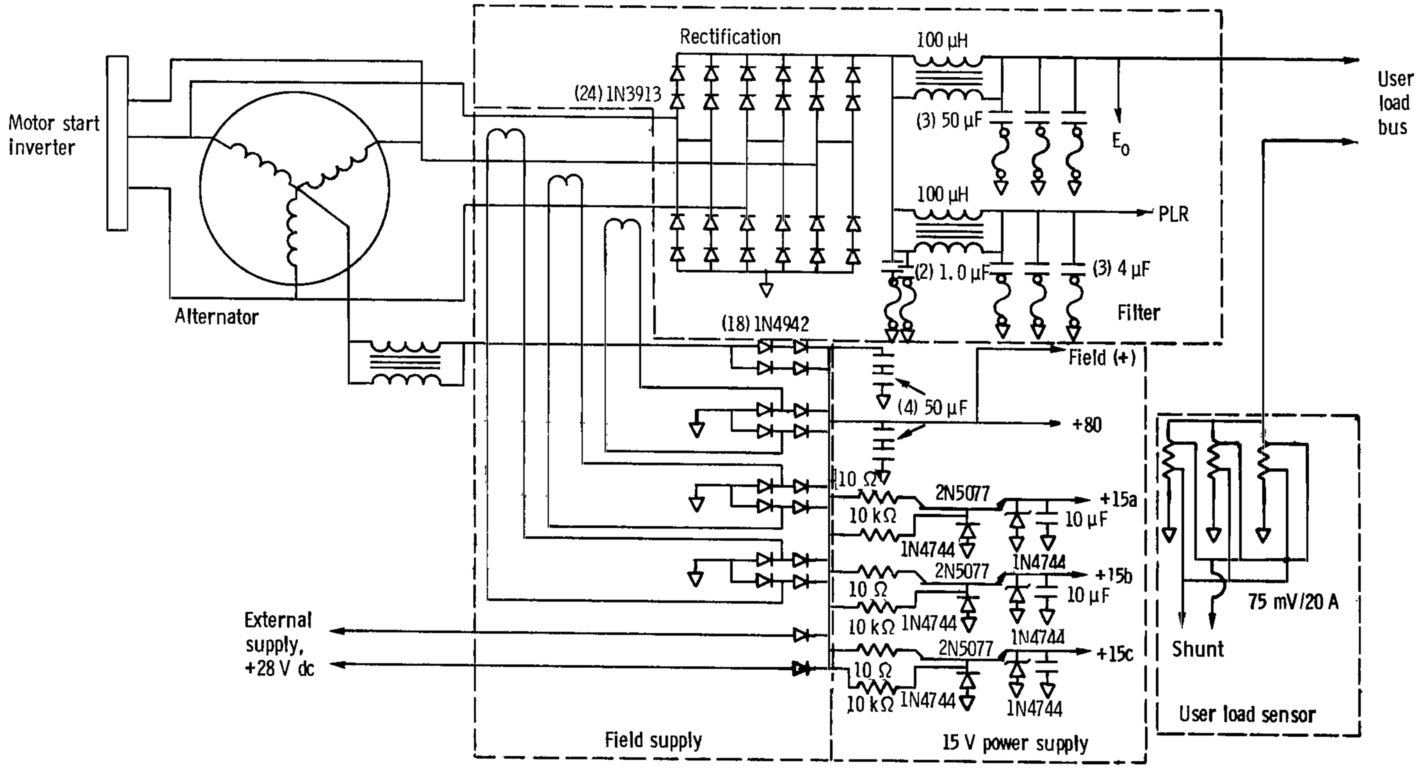
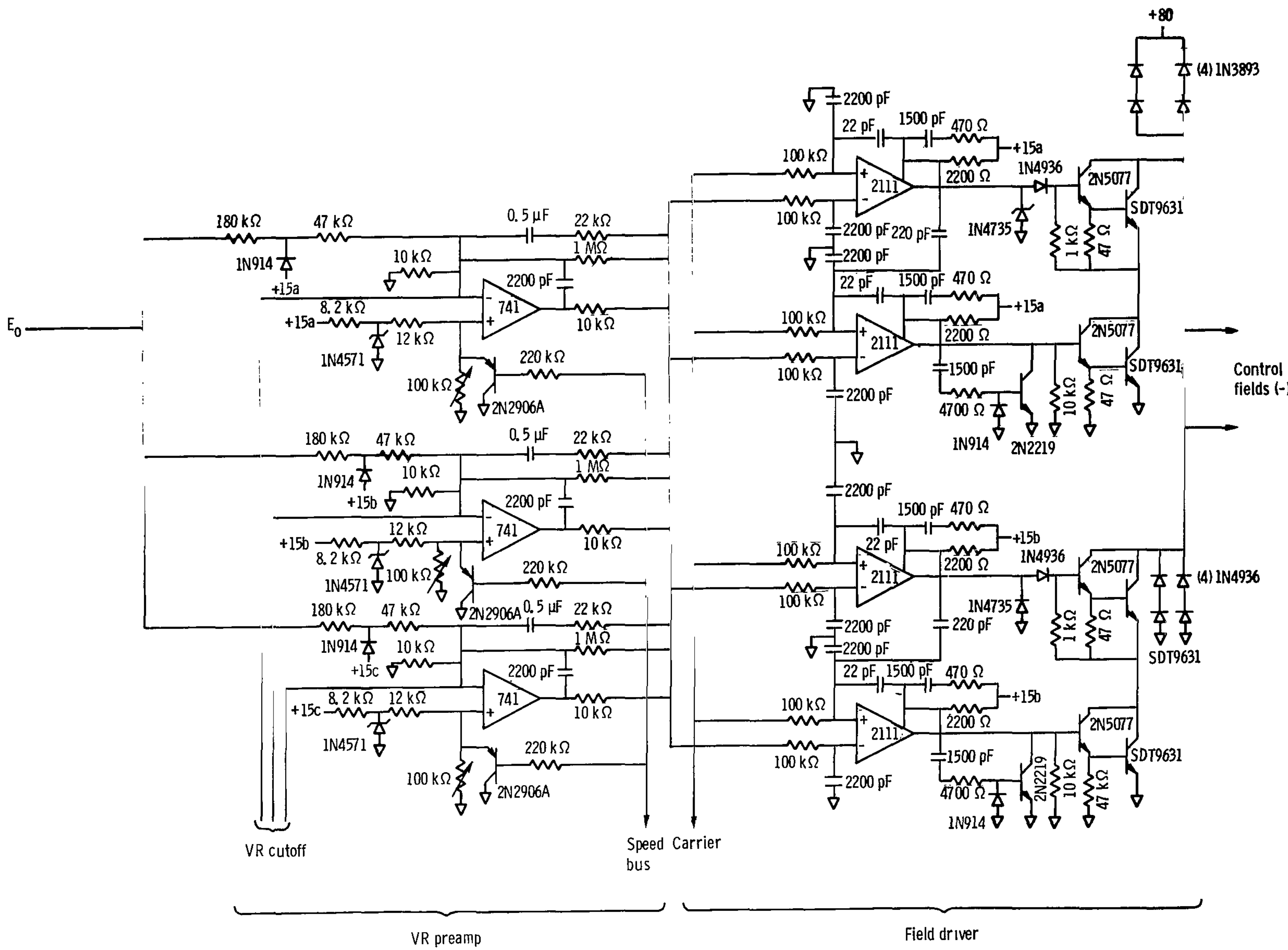


Figure 10. - Transient speed control characteristics.



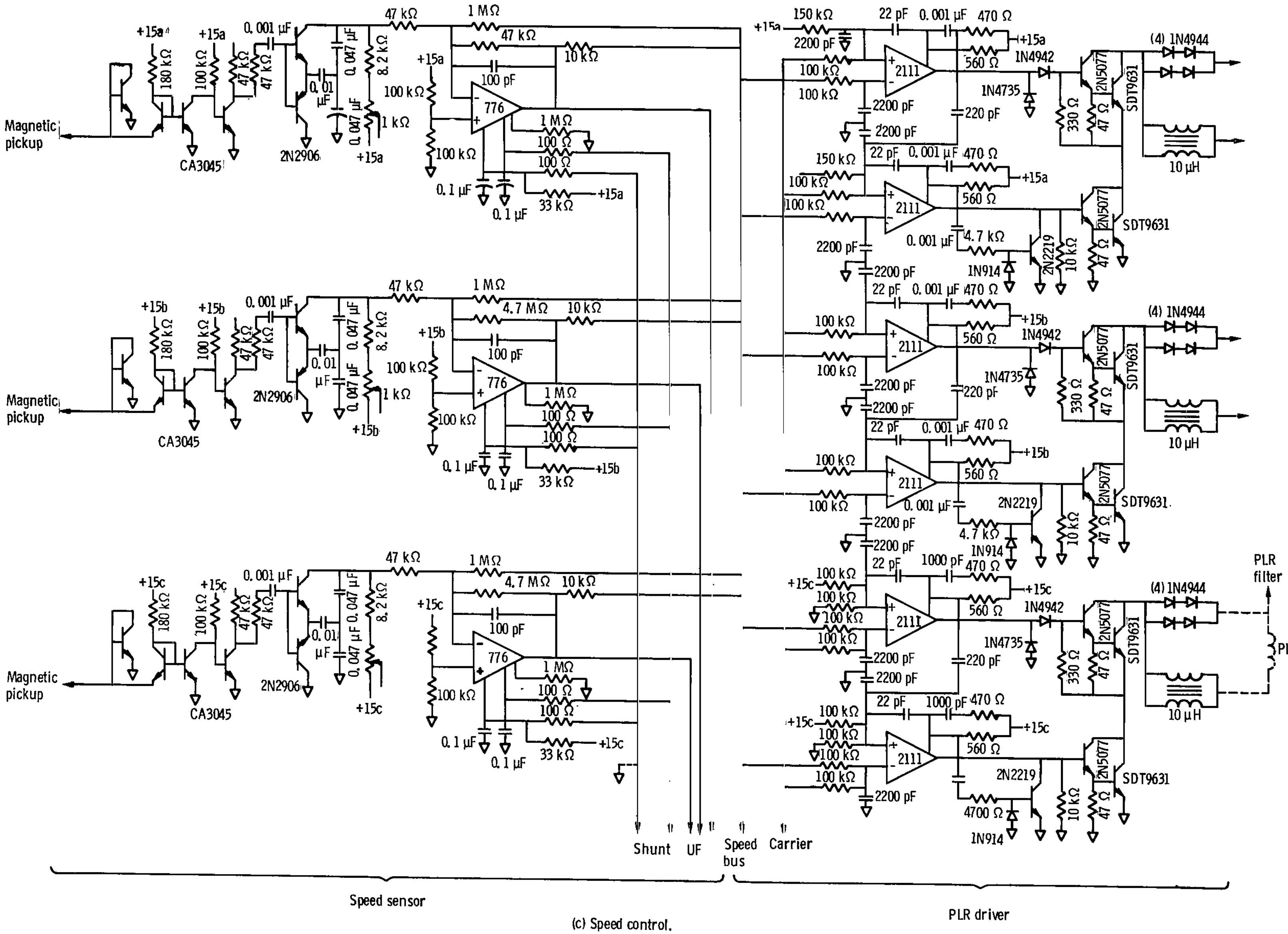
(a) AC-DC conversion, power supply.

Figure 11. - Control system schematic.



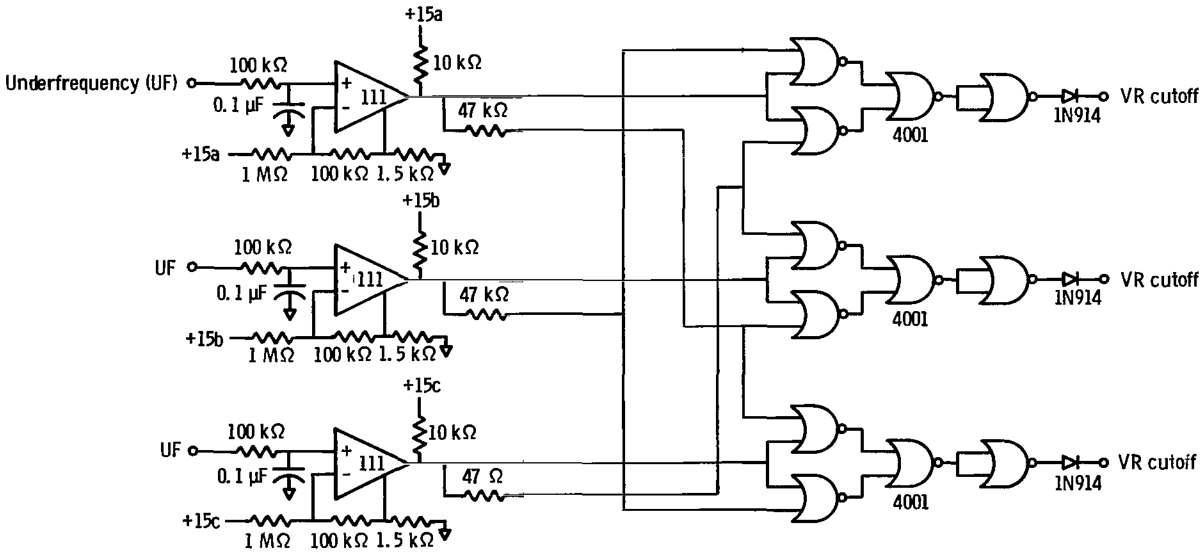
(b) Voltage regulator.

Figure 11. - Continued.

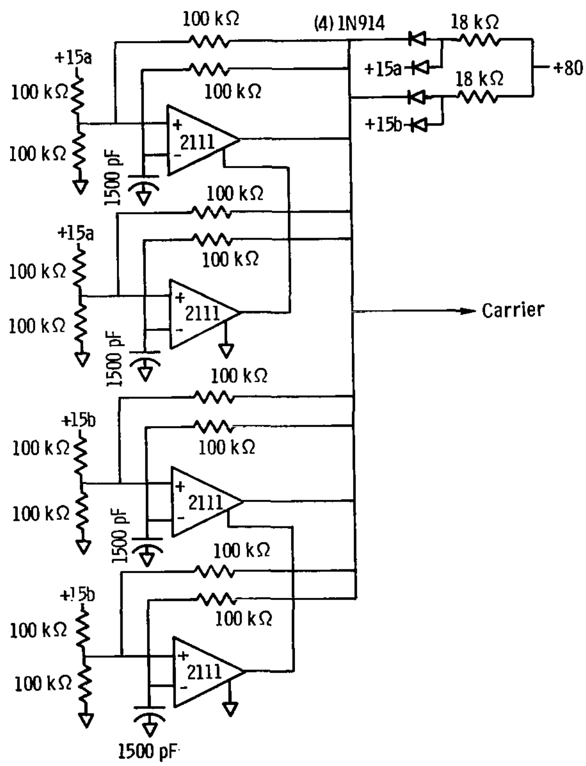


(c) Speed control.

Figure 11. - Continued.



(d) Underspeed voltage cutoff.



(e) Carrier generator.

Figure 11. - Concluded.

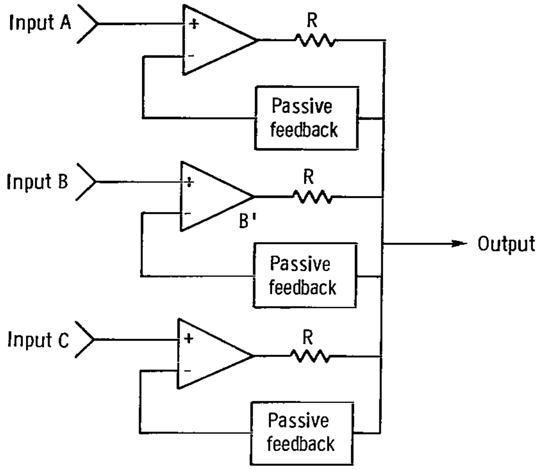


Figure 12. - Analog circuit redundancy configuration.

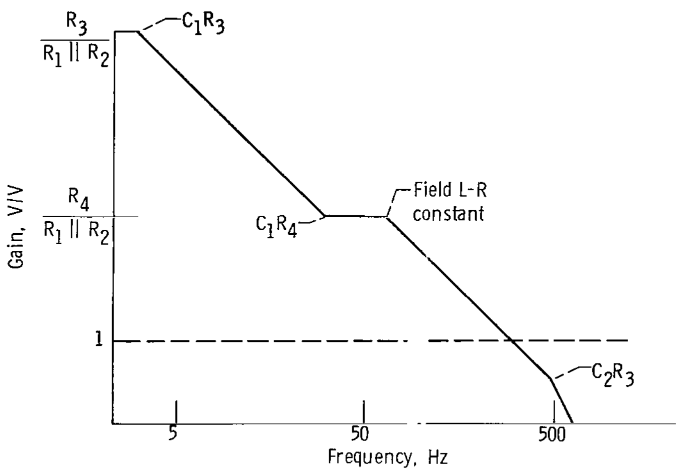


Figure 13. - Bode amplitude plot.

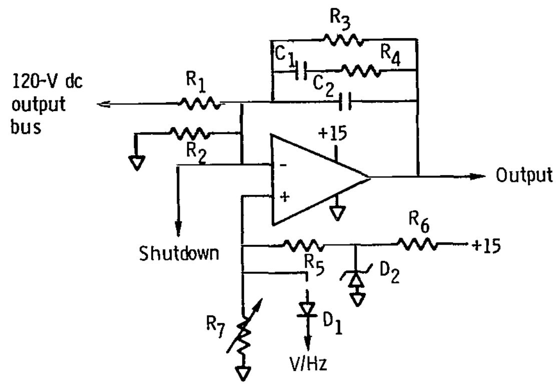


Figure 14. - VR preamp schematic.

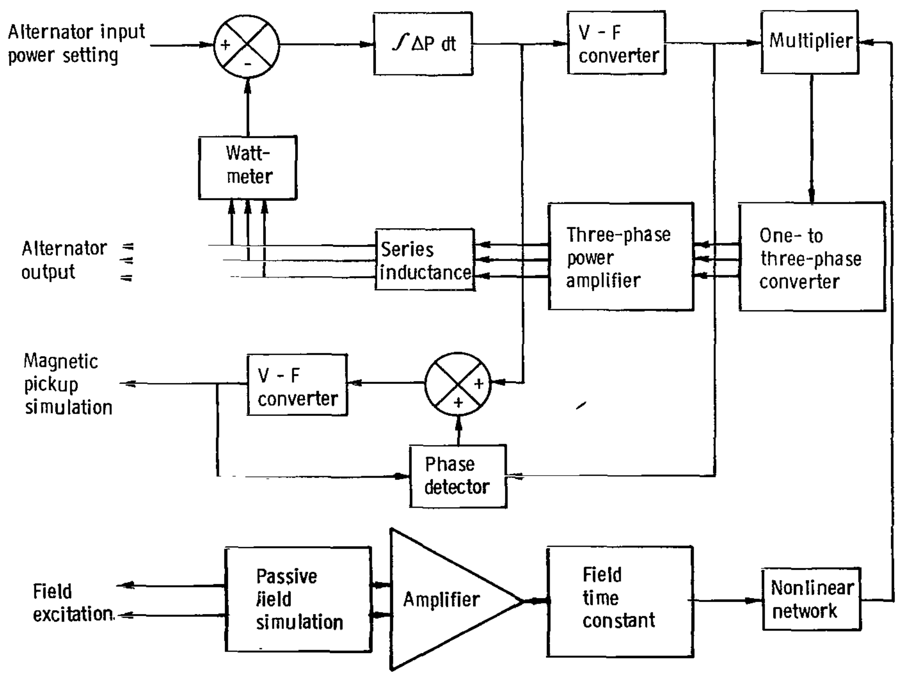


Figure 15. - Alternator simulator block diagram.

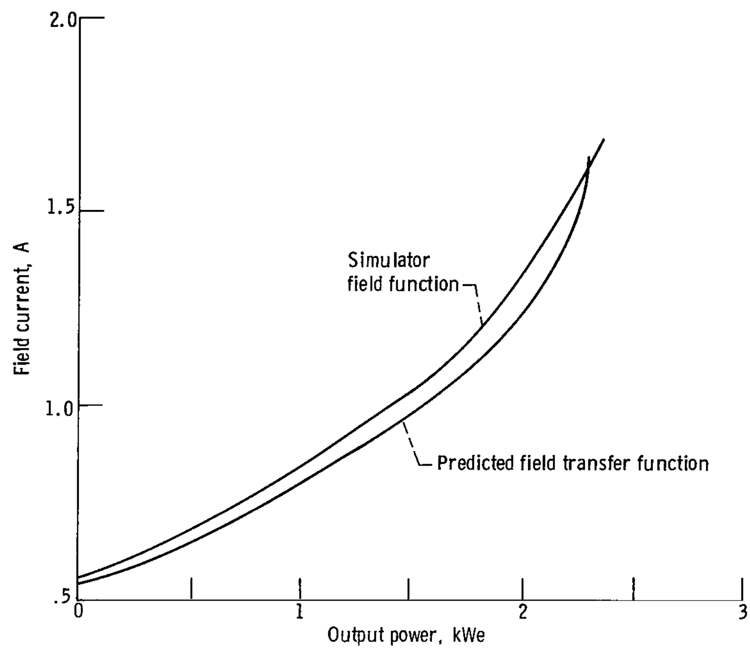
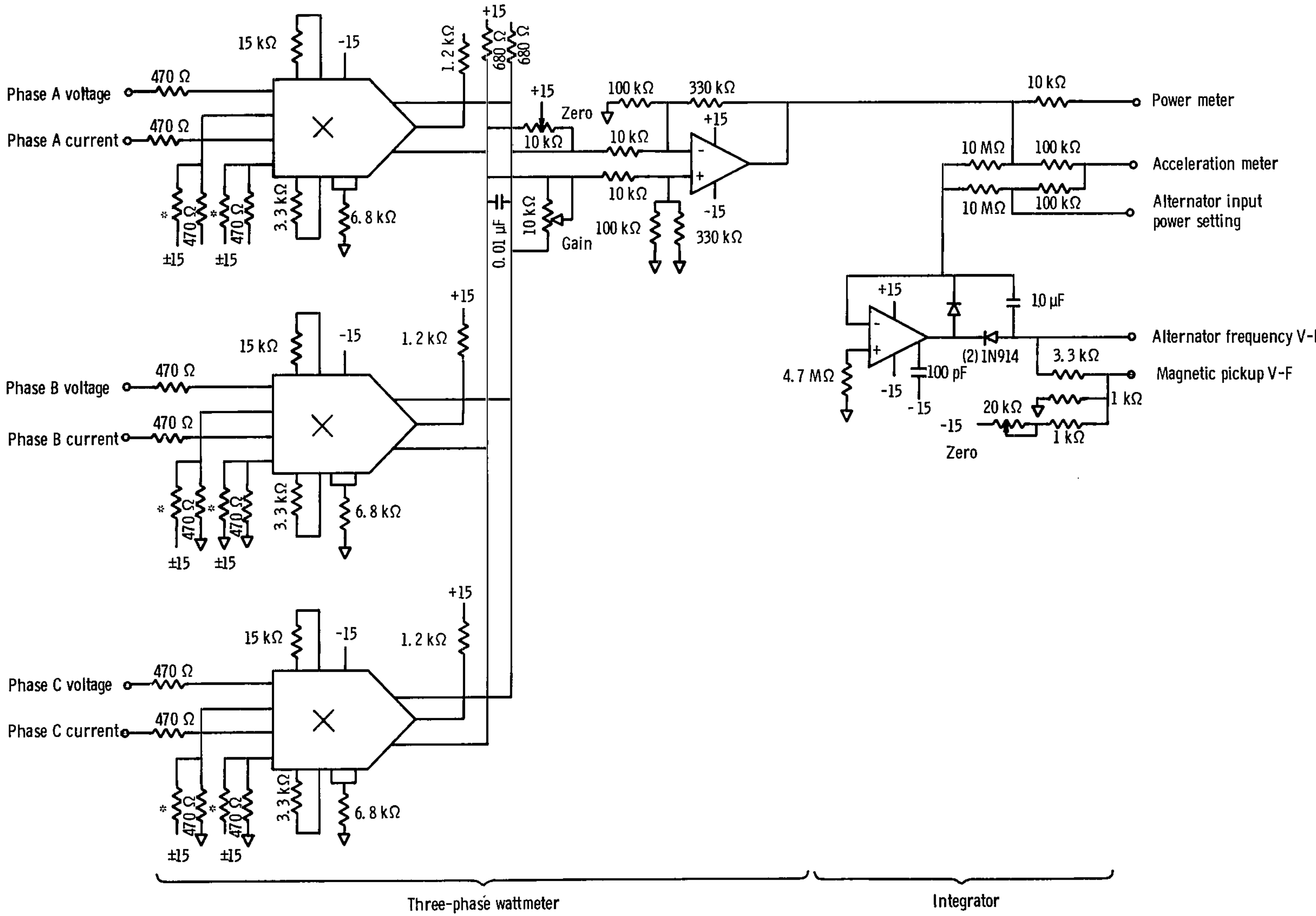
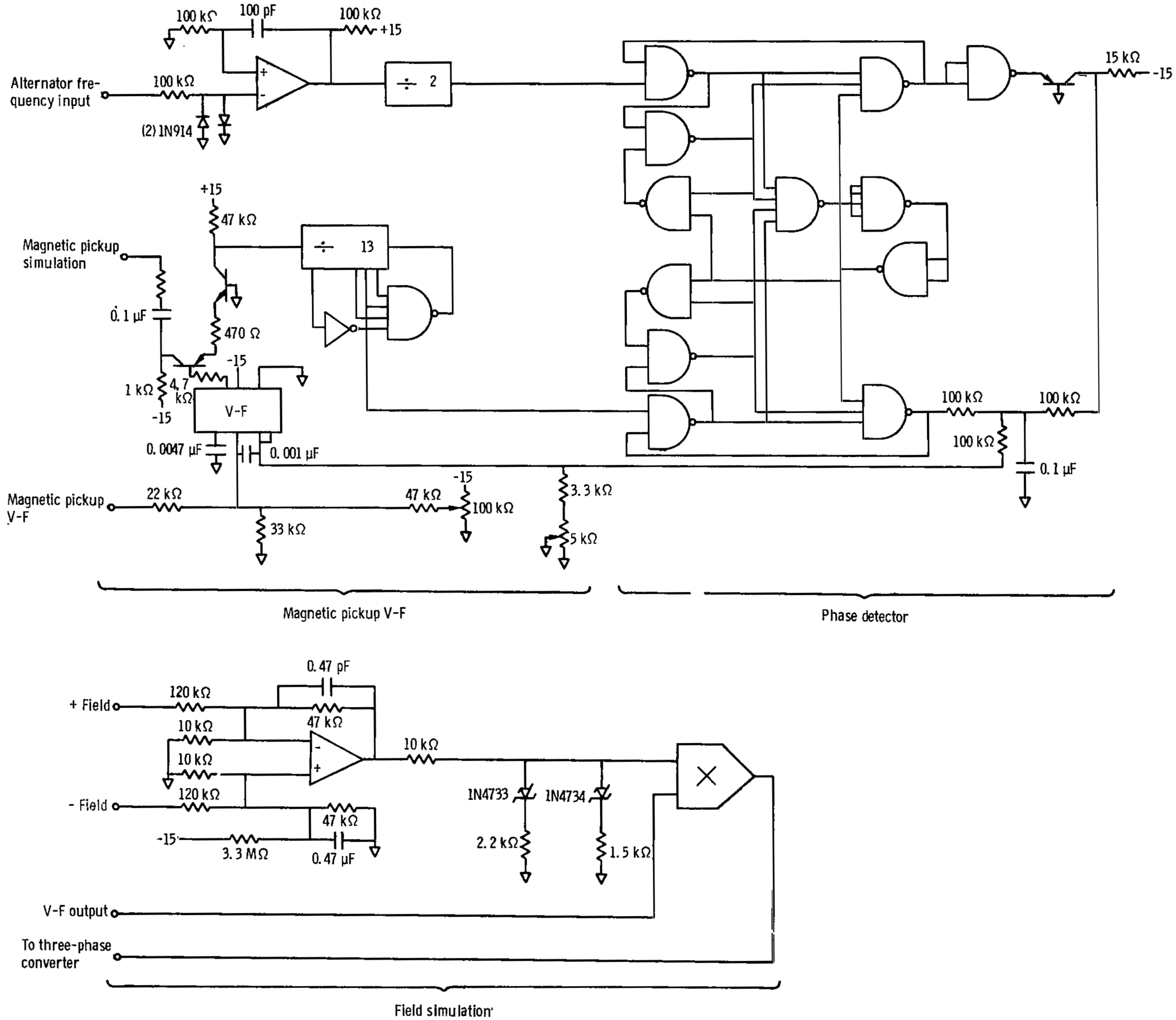


Figure 16. - Simulation of field function.



(a) Wattmeter and integrator.

Figure 17. - Alternator simulator schematic. (Asterisks denote selected trim value.)



(b) Magnetic pickup and field simulation.

Figure 17. - Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

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