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MARSHALL SPACE FLIGHT CENTER
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INVESTIGATION OF POTENTIAL DRIVER MODULES AND TRANSMISSION LINES FOR A HIGH FREQUENCY POWER SYSTEM ON THE SPACE STATION

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to NASA/ASEE for providing me the opportunity to participate in the Summer Faculty Fellowship Program at Marshall Space Flight Center. My first summer at MSFC has been very fulfilling and intellectually stimulating, due to the generous hospitality and assistance of my NASA counterpart, Mr. John R. Lanier and his team. Special thanks goes to Mr. David Weeks for his valuable information and suggestions. Discussions with Mr. Robert Kapustka were very valuable and helpful. I learned much from these discussions and I am very appreciative to him for taking time out to share with me his expertise.

Finally, I wish to thank Mrs. Shirley Butler for typing and correcting this report.

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ABSTRACT

The objective of this investigation is to assess the feasibility of using the Series Resonant inverter as the driver module for the high frequency power system on the Space Station. This study evaluates the performance of the Series Resonant driver when it was operated with a DC input voltage and run through a series of tests to determine its start-up performance, response to load changes, load regulation, and efficiency. Also, this study compares the Series Resonant driver to another kind of driver that uses a Power Transistor snubber.

An investigation of the various types of transmission lines is initiated. In particular, a simplified approach is utilized to describe the optimal transmission line.

INTRODUCTION

The original Space Station, Skylab, didn't require power at the levels of hundreds of kilowatts. In fact, Skylab used an 8 kilowatt bus for power distribution. In contrast, the Initial Operational Configuration (IOC) Space Station will require 75 kilowatts for primary power distribution while the growth Space Station will require 300 kilowatts. The spacecraft being designed for new NASA missions are projected to have demands for power at orders of magnitude greater than current Spacecraft. The evolving spacecraft power systems for these missions will require increased efficiency and versatility to meet load requirements of greater power, multiple users and increased life. Therefore, Space Station must have the ability to be expanded to cover expected power needs of hundreds of kilowatts.

NASA/Lewis Research Center has proposed to use a high-frequency, high-voltage AC power system to fulfill the needs of the Space Station. LeRC, the NASA center responsible for primary power generation and conditioning on the Space Station proposes to generate the AC power using a resonant AC power system. Furthermore, they are proposing a primary power distribution of 440V AC RMS single phase at 20 kilohertz, and part of this is to be distributed in the common modules.

Marshall Space Flight Center who is responsible for distributing power in the common modules have expressed deep concerns about this AC power system efficiency, transmission reliability, and corona effects inside the module. They have a special concern about using the series resonant inverter as the driver for the power system, and feel that this matter should be resolved before the final decision is made to build the system.

The resonant inverter was tested in a resonant AC power system test program that was developed by General Dynamics, a contractor for LeRC. The test results are utilized to evaluate the performance of the resonant inverter in a resonant AC power system.

1.0 SYSTEM TEST CONFIGURATION

1.1 AC System Operation

The basic circuit for the inverter is a simple series resonant circuit as shown in Figure 1-1a. The operation is as follows. When switch S1 is closed, the resonant circuit is excited and "rings" at the natural resonant frequency of the circuit determined by the values of L, R, and C. The voltage across the load will appear as in 1b. The load resistance dissipates energy from the resonant circuit and causes the voltage and current waveforms of the circuit to be damped. If the resonant circuit is now excited from a pair of opposite polarity sources through a pair of toggled switches operating at natural frequency (Figure 2a), a sustained AC wave can be developed as shown in Figure 2b.

This circuit can be implemented in the usual bridge arrangement depicted in Figure 3. Alternatively, the load can be placed in parallel with the resonant capacitor as proposed by Neville Mapham (Figure 4).

The current in the resonant circuit of the inverter is primarily determined by the L and C of the tank circuit. Therefore, the Mapham type inverter is a voltage source device because the load is in parallel with the resonant capacitor. The Mapham inverter is a voltage source but becomes overdamped and begins to operate irregularly for heavy loads. Because the AC breadboard is a utility-type power system the Mapham configuration was chosen as the driver module.

If the resonant frequency of the inverter is increased above the switching frequency then Silicon Controlled Rectifiers (SCRs) can be used as switches. Replacing the load resistor of Figure 4 with a transformer allows the inverter to be used as the driver to a high-voltage bus capable of providing power to a variety of loads. Larger power systems are possible by combining multiple inverter modules.

To test the Mapham topology, a resonant AC series inverter was operated with a DC input voltage and ran through a series of test to determine its start-up performance, response to load changes, load regulation and efficiency. The test results are discussed in the following sections.

1.2 Single Inverter (Configuration)

The test configuration was a 1.0 kw inverter module with a resistive load (Figure 5). The inverter schematic is in Figure 6. This module was operated with a 90-volt input and run through a series of tests to determine its start-up performance, response to loadchanges, loadregulation, and efficiency.

2.0 TEST RESULTS

2.1 Start Up of a Single Inverter

The test circuit for the single inverter is shown in Figure 7 and the inverter schematic in Figure 6. For this test configuration, the SCR firing signals were enabled prior to the closing of the relay. The oscilloscope was triggered as the relay coil was energized. The inverter was able to start up in this manner under all load situations except full load (1.1kw). When the 1.0kw inverter was step-started under full load conditions (1140w), the resonant circuit responds as if it were overdamped. This caused one pair of SCRs to be triggered while the current in the other pair of SCRs has not yet returned to zero (See Figure 6). The result was a shorting of the input.

In brief, the test results indicated that a single inverter in a resonant power system configuration exhibited no problems starting up with a step application of voltage while under no load to 50% resistive-load conditions.

2.2 Steady-State Operation of a Single Inverter Module

A schematic of the 1.0kw-inverter module is shown in Figure 6. The currents and voltages referred to in this section are labeled in the figure. Figure 8 shows the leg current of the inverter and its output voltage for the 0.0kw case and the 1.1kw case. The positive portion of the leg current is the current in the SCR and the negative portion is the diode current (reverse current).

As shown in Figure 8, it is apparent that the inverter output voltage amplitude does not change much with load. In fact, the graph of the output voltage versus the load power (Figure 9) indicates that the inverter is a stiff voltage source. Over the range of 0.0 to 1.14kw, the output voltage of the inverter decreased from 124V RMS to 117V RMS. This yields a load regulation of 6% for the unregulated inverter. At 1220w, the voltage was still at 114V RMS.

It is also apparent in Figure 8 that high frequency oscillations are present on the leg currents, and they changed with load.

As expected, since the triggering of the (SCRs) was controlled by a clock, the frequency of the inverter output changed very little with load. It was measured at 20.01 KHz while unloaded and 20.00 KHz with a load of 1220w. This was not the case for efficiency (Figure 10). With a 90 Vdc input the inverter was most efficient (96.8%) under-full load conditions. In conclusion, the single phase power system breadboard test demon stated that the resonant inverter was efficient and versatile as a system building block. The 1.0kw inverter breadboard was 96.9% efficient. The inverter supplied power over long distances (50 meters) to active load modules.

The development of inverters must also be continued. Since the majority of the power loss in an inverter was attributable to the SCRs, alternatives must be explored.

2.3 Transient Load Response of a Single Inverter

The inverter circuit is shown in Figure 6 and the circuit used to abruptly change the inverter load is shown in Figure 11. Three load changes were tested:

a. 0.0w to 580w and reverse
b. 580w to 1110w and reverse
c. 130w to 1110w and reverse

The most dramatic power change took place in the 130w to 1110-w case. Yet, the inverter experienced only a short and smooth transition period as shown in Figure 12 and 13, which show the inverter output voltage and current for the 130 to 1110-w and 1110 to 130-w case respectively. Discounting the switch bounce in Figure 12 these figures showed that the overshoot of the inverter was small and the entire transient response lasted only about 150 microseconds. The other inverter parameters such as the leg current (Figure 14) also showed a smooth and brief transition for abrupt load changes. The transient response characteristics in the other two cases (0.0w to 580w and reverse and 580w to 1110w and reverse) lasted for a shorter amount of time because the load variation was not as great.

2.4 Power Supply Sensitivity of a Single Inverter

The test circuit of Figure 15 was used togather both the transient and steady-state data on this configuration. The steady-state measurements of the power sensitivity are listed Table 1. Since the inverter is unregulated, its output voltage changes the same percentage as the input voltage, and the sensitivity is 1.0 as expected. In Table 1, the efficiency of the driver appears low because the inverter is only about 90% loaded.

In the transient case, the relays switch fast but when the input voltage was decreased, the settling time was determined by the time constant of the input capacitor (700 microforads) and the load resistance. Indeed there was a period of about 0.3 milliseconds when neither relay of Figure 15 was closed, and the input capacitor supplies all the power to the load. Figure 16 shows the input current to the input capacitor going to zero for 0.3 milliseconds.

In brief, the test results indicated that every parameter in the system showed a smooth transition. The shift to a higher input voltage was also a smooth transition, but its time constant was much longer and was determined by the response time of the power supplies.

2.5 Power Turn Off a Single Inverter

The relay used to remove the power from the inverter was placed after the input capacitor as shown in Figure 17. After the relay was opened, the input voltage became a square wave because there was no input capacitor to hold the input voltage constant. This voltage alternated between the resonant capacitor peak voltage (initially twice the input voltage) and zero at 40KHz as shown in the no-load case of Figure 18. The voltage decreased exponentially until the energy of the tank circuit was dissipated. The time constant of this decay became shorter as the inverter was loaded as shown in Figure 19, which shows the inverter output voltage for the no-load and the 580-w case. The remainder of the inverter parameters showed this same exponential decay.

In brief, the test results indicated that the output voltage of the inverter merely decayed to zero with a time constant based on the filter components and the load.

2.6 Conclusion

The testing of the single-phase, 2.0-kw resonant AC power system breadboard demonstrated that the resonant inverter was efficient and versatile as a system building block, but it needs to be developed more to get rid of the power losses attributable to the SCRs. Furthermore, the inverter must be more efficient for the AC power system on the Space Station, because it will have to drive high frequency AC power down the boom to the common modules. Therefore, Marshall Space Flight Center, who is responsible for development of power in the common modules, is concerned about using this resonant inverter as the driver for the AC power system.

3.0 MSFC CONCERNS

3.1 Propagation of Fault to Series Resonant Inverter

If a fault in the system propagates back to the SRI the bus collapses and the system goes dead. MSFC feels that a utility-type power system should be built to provide power to remove the fault.

3.2 Efficiency at Partial Loading Due to Redundancy Schemes

LeRC efficiency projections involving SRI are based on full loading. MSFC feels that the projections should be based on 50% loading.

3.3 Corona Effect

For the Space Station LeRC is proposing a primary power distribution of 440Vrms single phase at 20 kilohertzs. MSFC, who is responsible for the development of the electrical power system in the common modules is concerned about the power distribution in the modules, because the modules are suceptible to corona at high voltage and twenty kilohertz frequency. Therefore, they are planning to reduce the voltage outside the common modules by using a step down transformer.

3.4 The AC Power System Efficiency Dependence

The test results from the AC power system test program indicated that the AC power system efficiency depended much on the resonant inverter efficiency. The test results indicated the efficiency of the power system depended on the frequency of the resonant inverter. In a resonant inverter, the resonant frequency of the reactive components is higher than the switching or line frequency. It was shown that when the two frequencies were brought closer together, the stoed energy in the reactive component increased. This increased energy increased the current in the inverter causing the resistive power losses to rise as the square of the current while the output power rose linearly with the current. Thus, the efficiency of the system was reduced.

By tracing system losses, it was learned that significant power was being dissipated in the resonant capacitor. A closer look revealed that much of the losses were caused by Eddy currents being induced in the cases of these capacitors. While desiging and testing sample transmission lines it was learned that adding the shield to the transmission line increased the line resistance and thus the power dissipation of the line. It turned out that this additional power loss was attributed to Eddy currents being induced in the shield from the current in the line. The power in these Eddy currents had dissipated in the resistance of the shield.

In brief, reduction in efficiency was attributed to the power losses in the transmission line.

Conclusions and Recommendations

Based on these concerns MSFC feels that alternate approaches to the SRI should be investigated, and that a thorough investigation of transmission lines should be initiated, before the AC power system is built. Therefore, Bob Kapustka, a power electronics expert at MSFC, has proposed alternate approaches to SRI. Also, he has been measuring various wires to determine their transmission characteristics.

Part of my research time has been spent measuring and testing wires. The results are shown in Table 1 and Table 3. The test configuration is shown in Figure 20. The other part of my research time has been spent analyzing and evaluating the test results from the resonant AC power system test program. Based on these research experiences, I agree with MSFC that the AC system should be made more efficient before it is built. Therefore, I make the following recommendations:

a. More wires should be tested.

b. Time and money should be given to Kapustka to build and test his topology in AC power system.

c. The MSFC AC power breadboard should be used as test facility for power converters and transmission lines.

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TABLE 1

POWER SUPPLY SENSITIVITY OF THE INVERTER

V_{in} (v_{dc})	I_{in} (A_{dc})	V_{out} (V_{rms})	I_{out} (A_{rms})	f(khz)
69.6 -20%	10.20	93.0	6.9	20.0
87.0	12.76	117.0	8.6	20.0
104.4 +20%	15.24	140.6	10.2	20.0

TABLE 2

WIRE TEST RESULTS AT 20 khz

WIRE #	NUMBER OF FEET	ESL (uH)	ESR (mΩ)
20	2.5	216.9	58.9
16	1.5	.4538	6.02

ESL/ ESR/\Z\ FOR 10 FT.

	LOOSE (3 in SPACING)	TOGETHER NOT TWISTED	TWISTED(2-3 TURNS/FT.)
	ESL(uH)/ESR(mΩ)/\Z\(mΩ)	ESL(uH)/ESR(mΩ)/\Z\(mΩ)	ESL(uH)/ESR(mΩ)/\Z\(mΩ)
12	5.4 /52 /681	2.4 /52 /306	1.6 /59 /209
SINGLE SHIELDED	7.2 /172.05 /472	4.2 /172 /	3.4 /179.07 /468.63

TABLE 3

TEST RESULTS OF VOLTAGE LOSSES
FOR 10 FT. OF #12 WIRE

WIRE ARRANGEMENT	INPUT VOLTAGE	OUTPUT VOLTAGE	LOSSES
PARALLEL	143.0	142.6	.4
	144.4	144.0	.4
	143.2	142.4	.8
	144.4	144.2	.2
	147.4	144.6	.8
TWISTED TOGETHER (2-3 TURNS/FT.)	148.2	148.0	.2
	147.4	146.2	1.2
	146.8	143.6	3.2
	149.4	147.6	1.8
	152.0	150.2	1.8

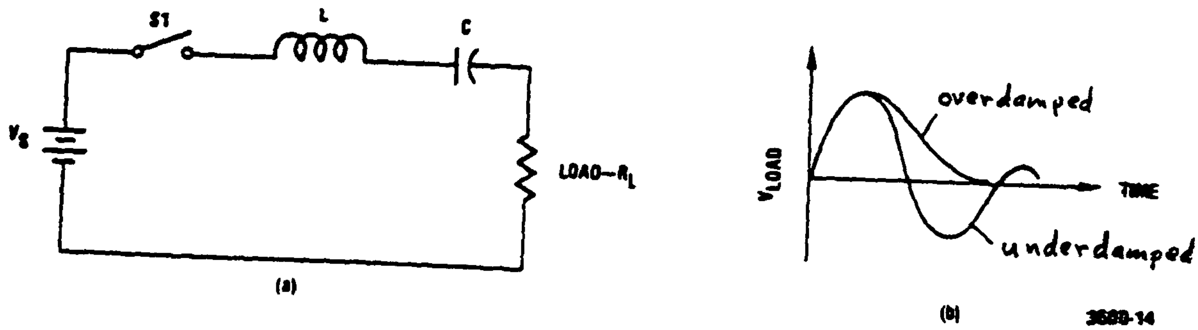


Figure 1. Basic Series Resonant Circuit

Figure A-1. Basic resonant circuit.

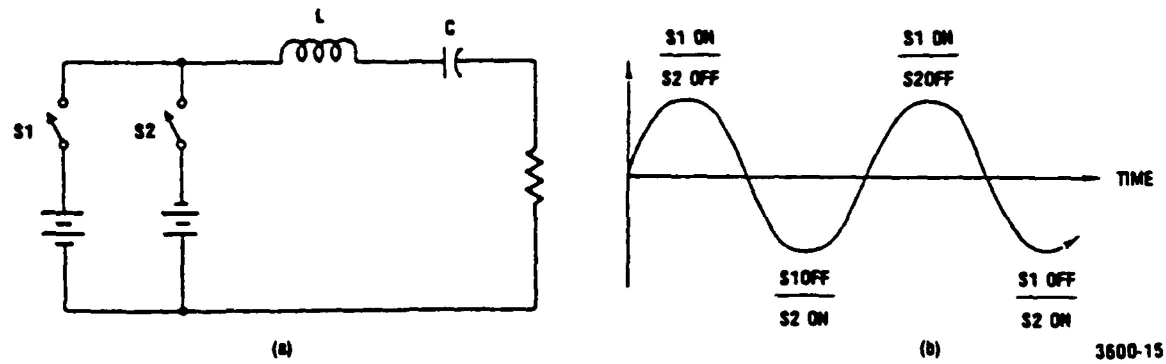


Figure 2. Dual-Polarity Series Resonant Circuit

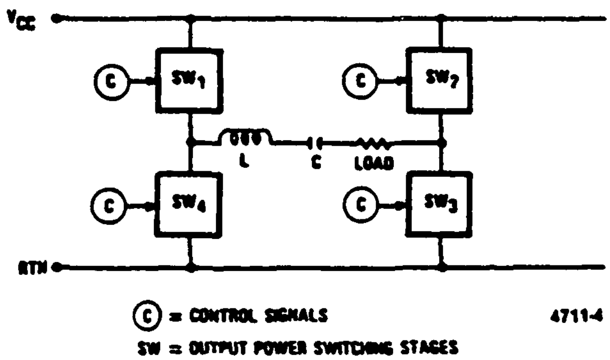


Figure 3. Series - Output Type Series Bridge Circuit

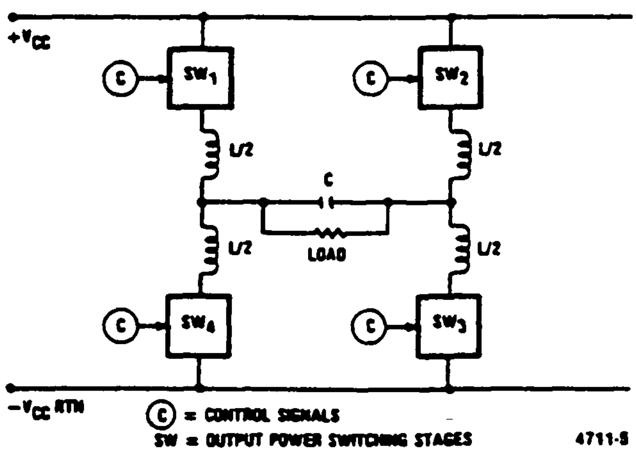


Figure 4. Parallel - Output Type Series Resonant Bridge Circuit

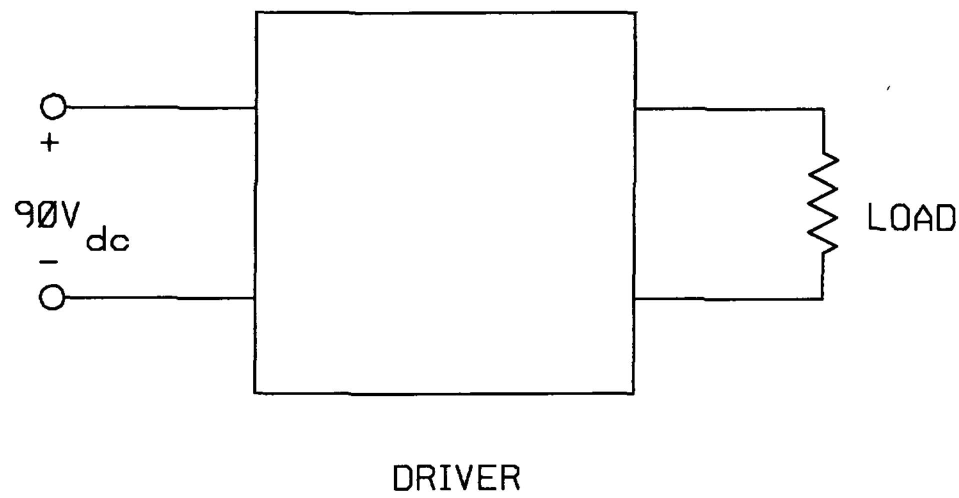
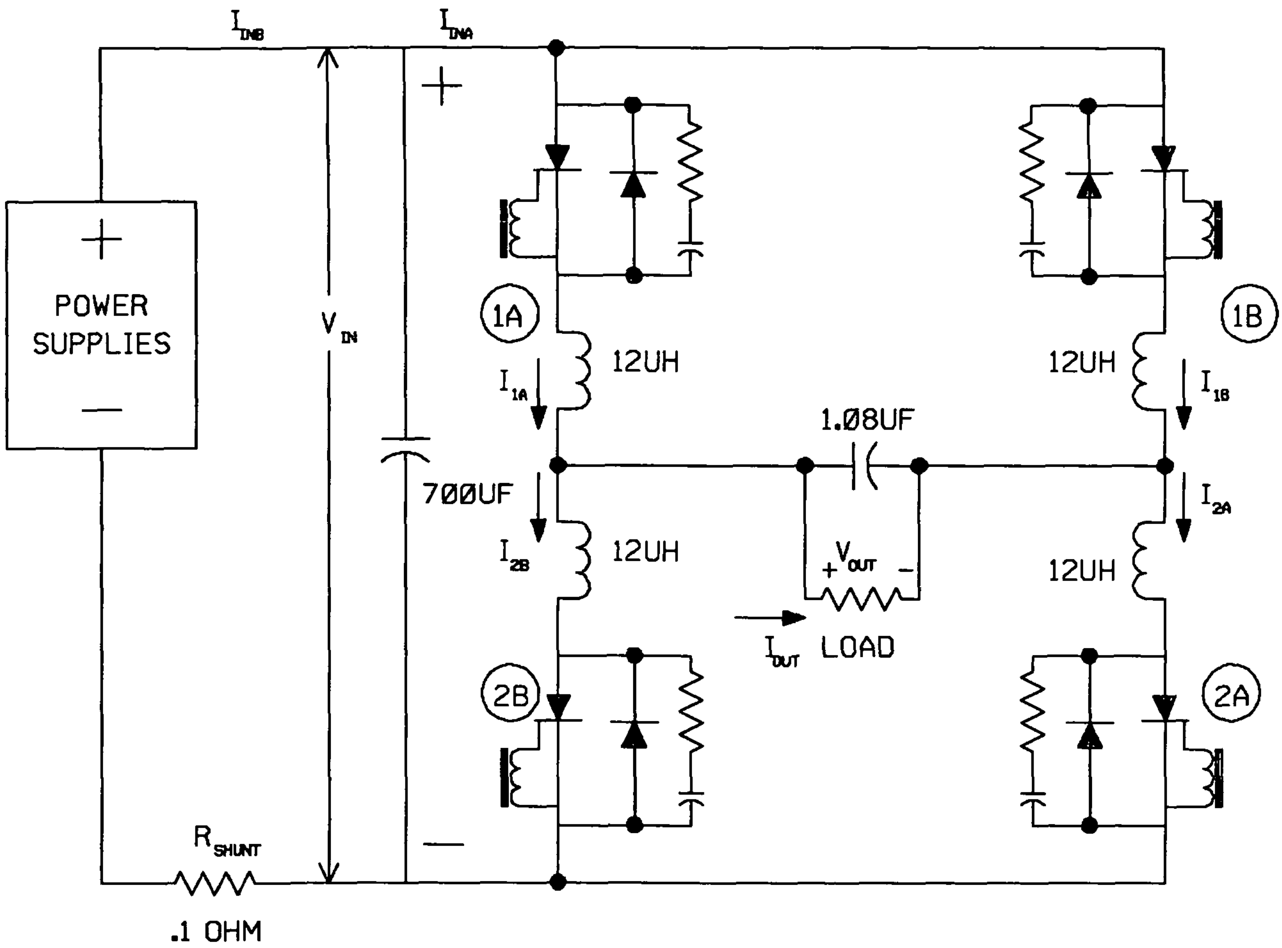


Figure 5. Test Configuration Driver with Resistive Load

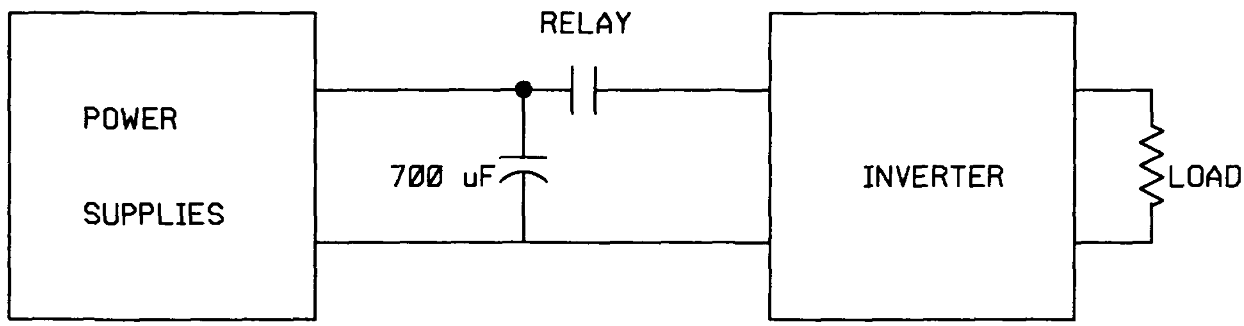


SCR'S =2N3658

DIODES =A139M

SNUBBERS =110OHM/.01UF

Figure 6. 1.0kw Inverter Schematic



LOCATION OF POWER RELAY

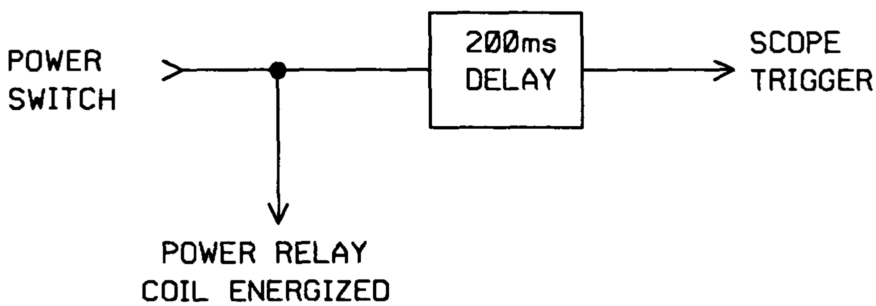


Figure 7. Start Up Circuit for Single Inverter Configuration

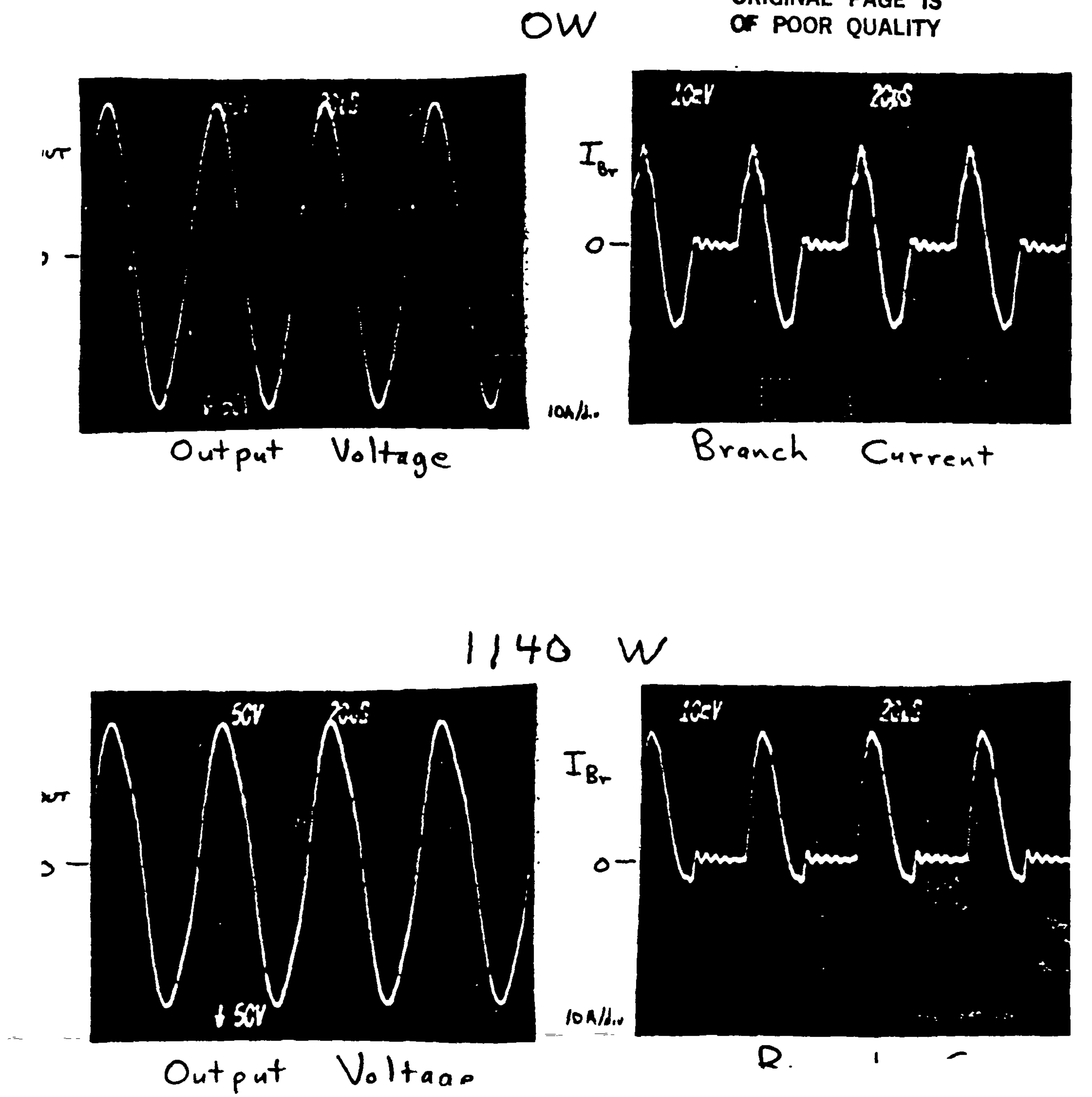


Figure 8. Inverter Leg Current, with no load and a 1.1kw load

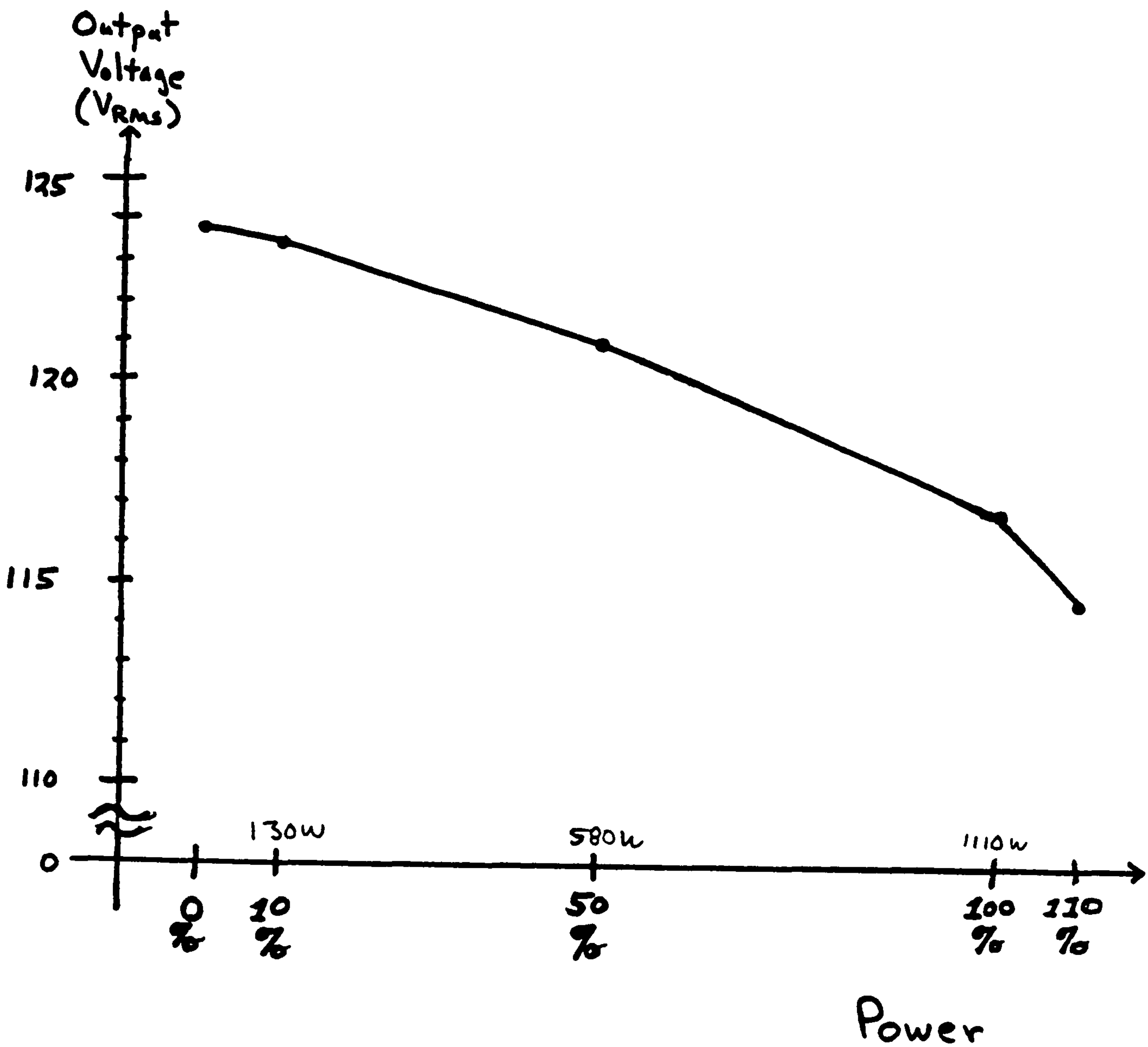


Figure 9. Output Voltage Versus Load Power

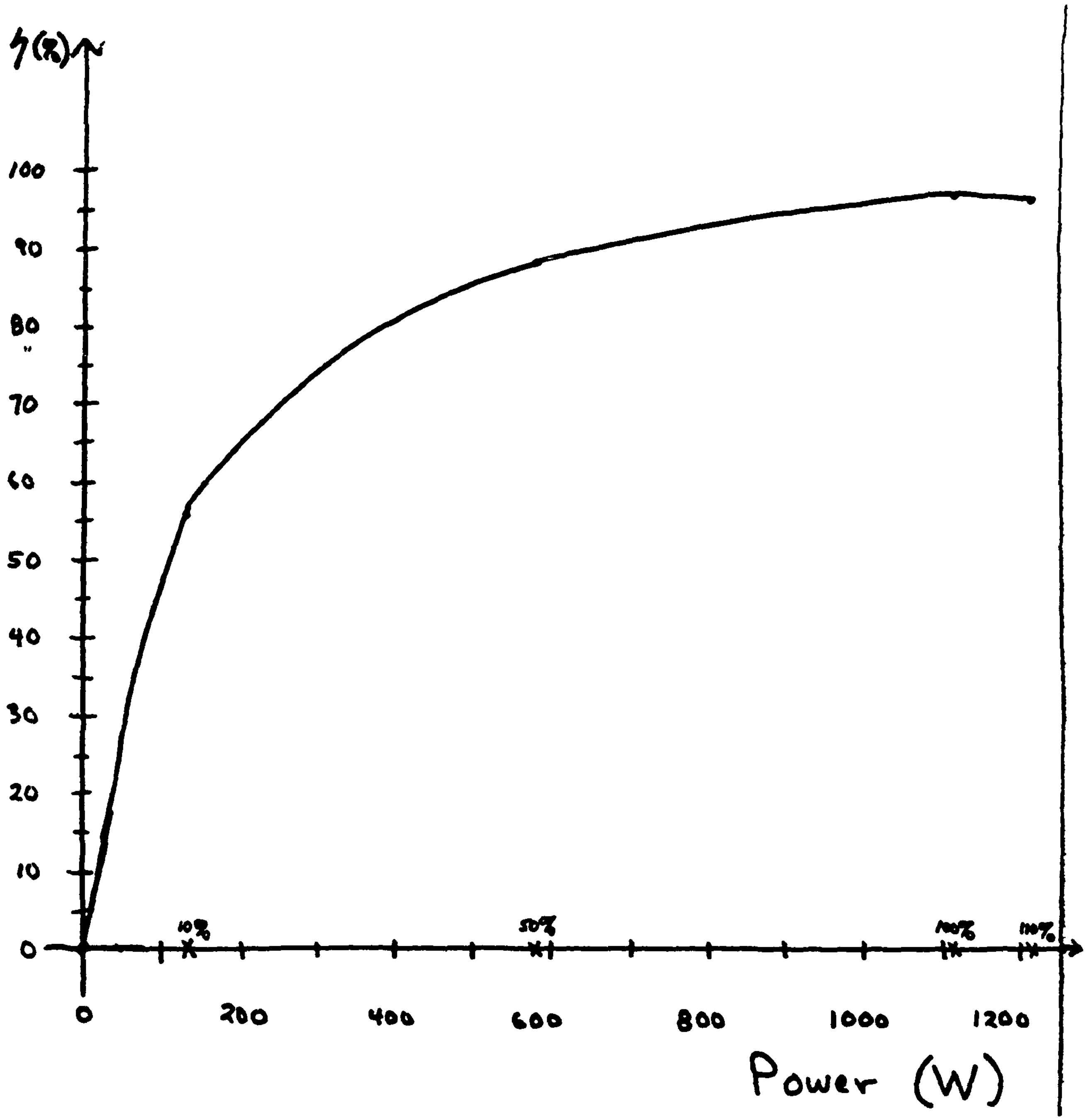


Figure 10. Efficiency Versus Load Power

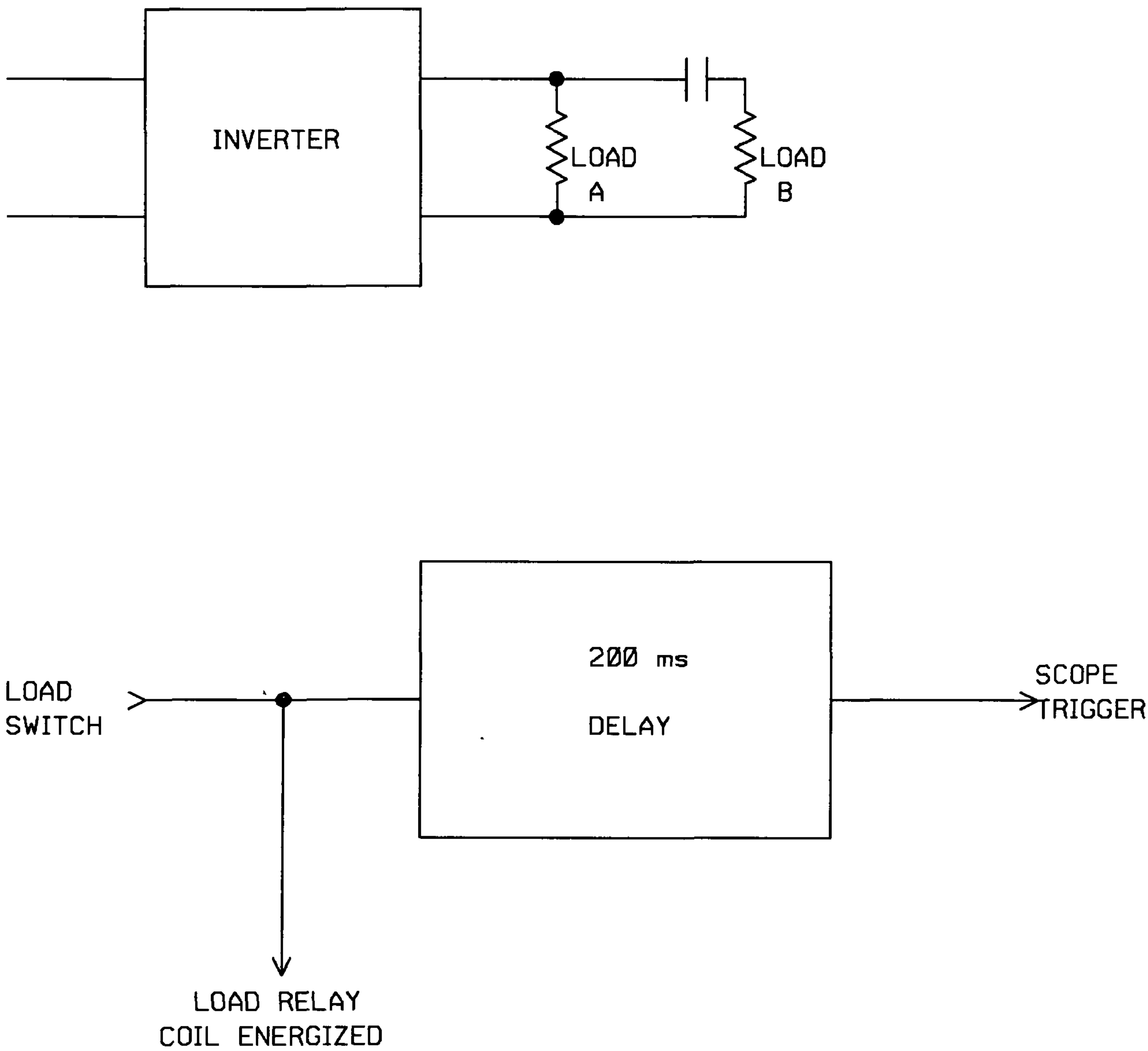


Figure 11. Test Circuit to Measure Transient Load Response of a Single Inverter Module

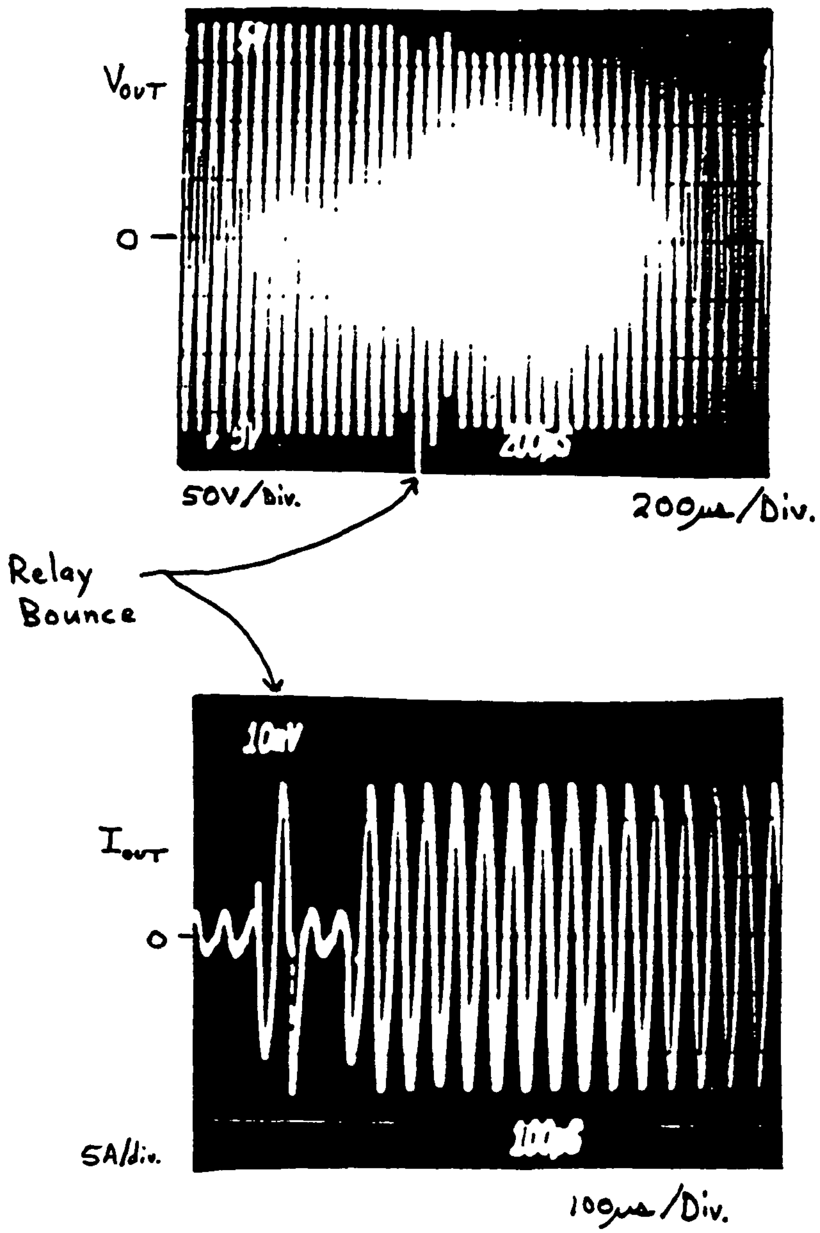


Figure 12. Inverter Output Voltage and Current as the Load is Switched from 130w to 1110w

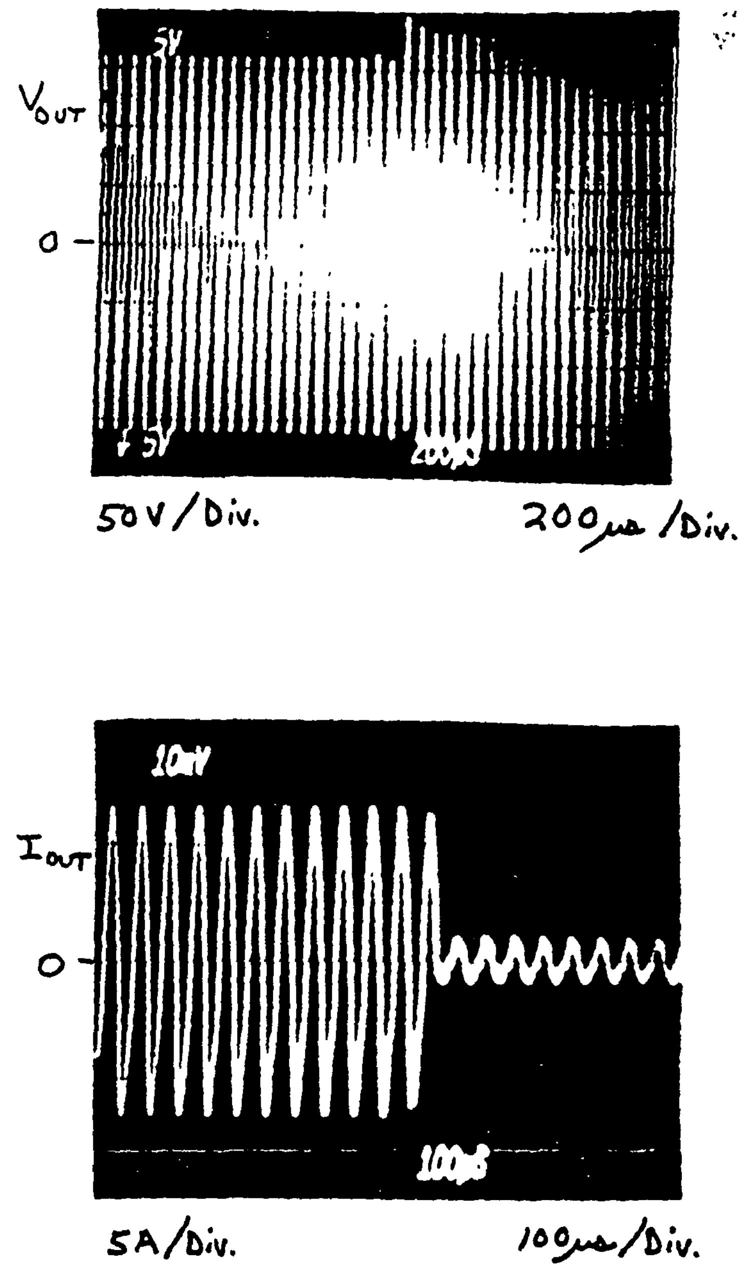


Figure 13. Inverter Output Voltage and Current as the Load is Switched from 110w to 130w

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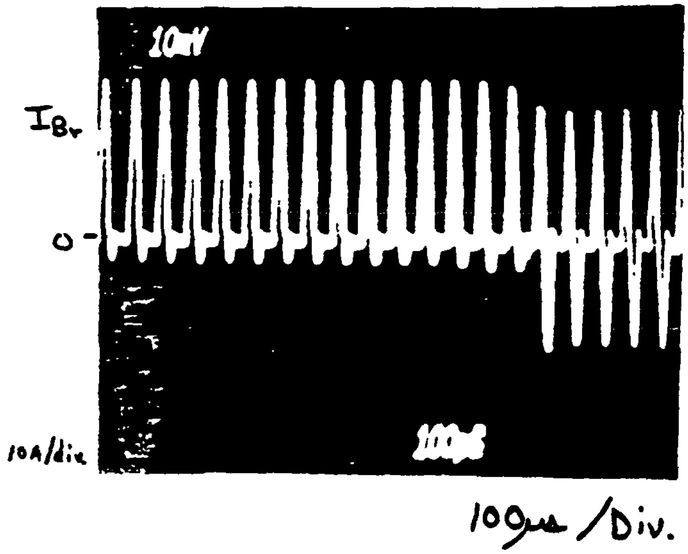


Figure 14. Inverter Leg Current as the Load is Switched from 110w to 130w

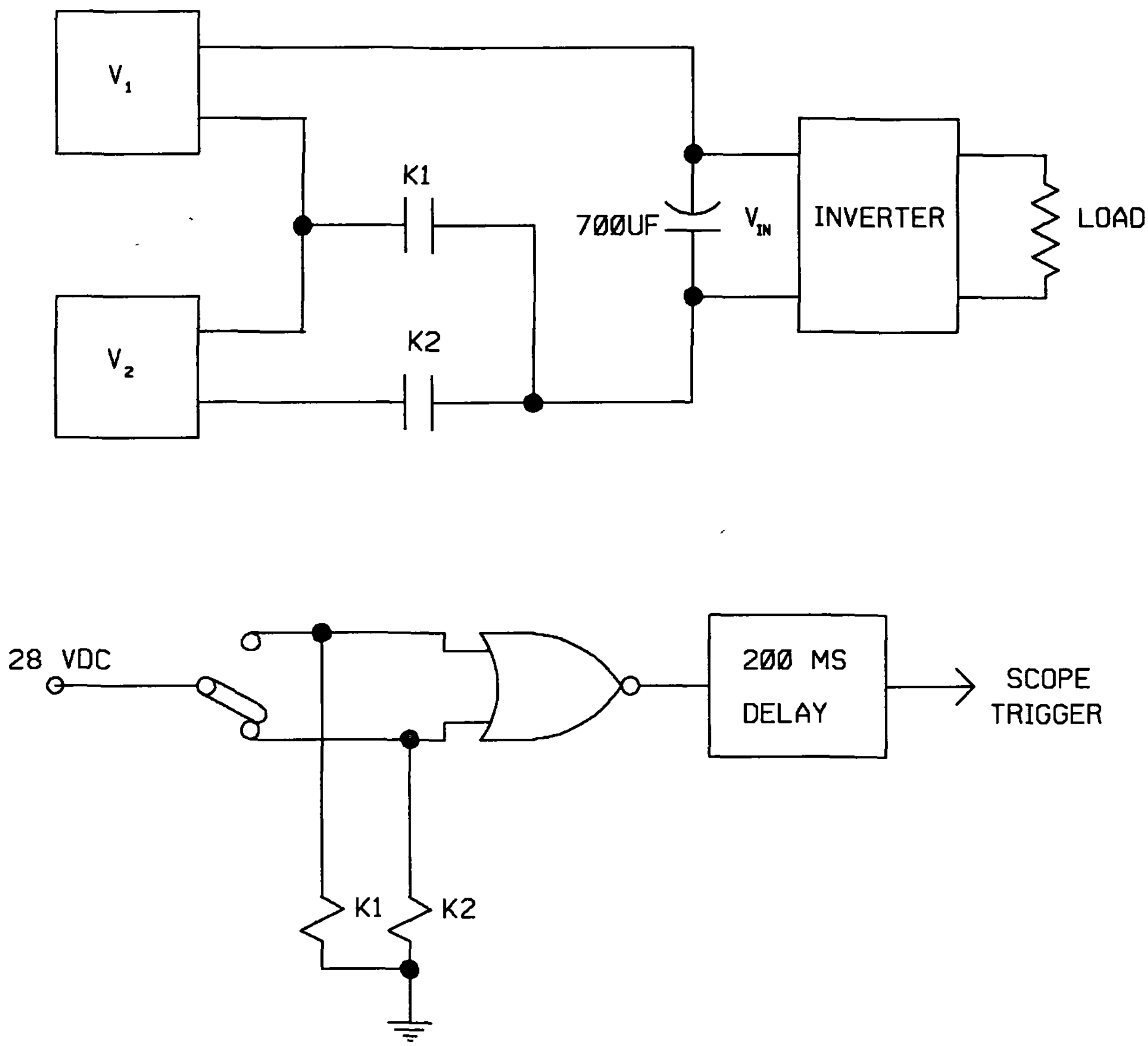


Figure 15. Test Circuits for Power Supply Sensitivity Measurements of the Inverter

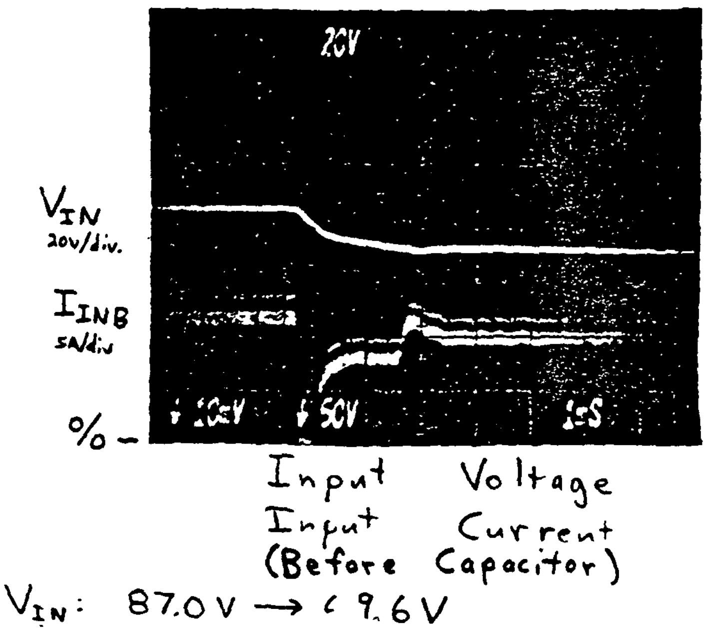
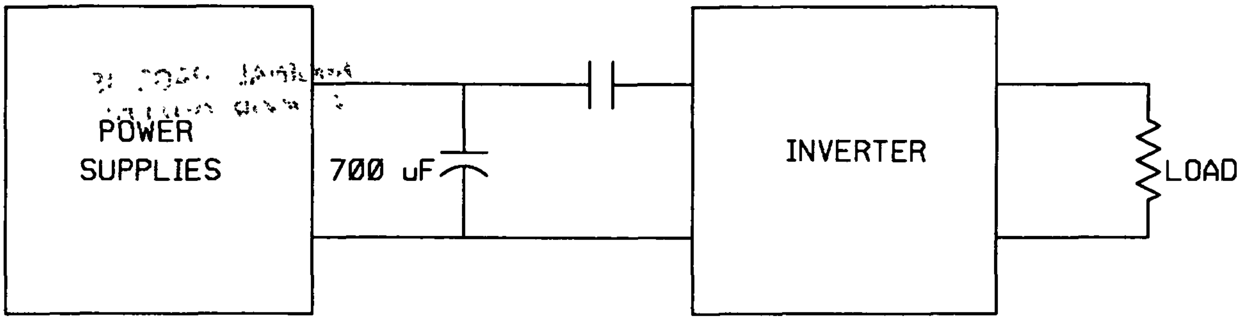


Figure 16. Input Parameters of the Inverter as the Input Voltage is Switched from 87.0Vdc to 69.Vdc



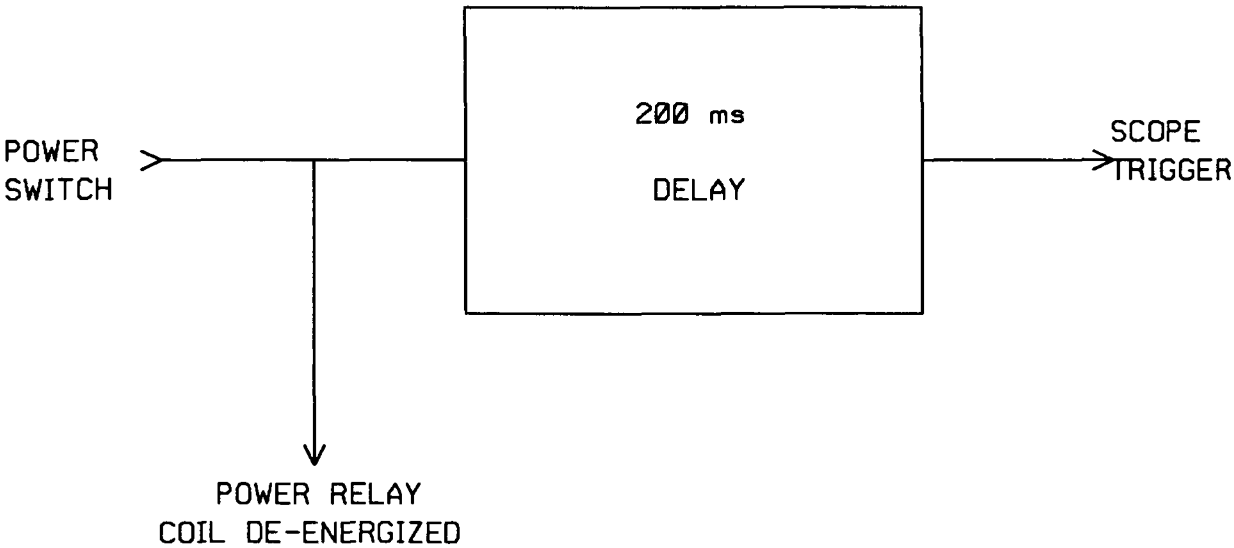


Figure 17. Circuit Used to Gather Data for the Single - Inverter Case of Power Turn Off

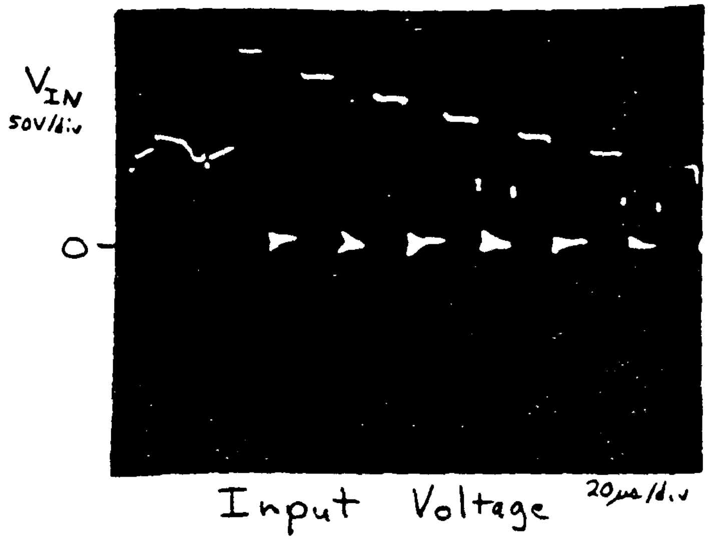


Figure 18. Input Voltage as the Power is Turned Off

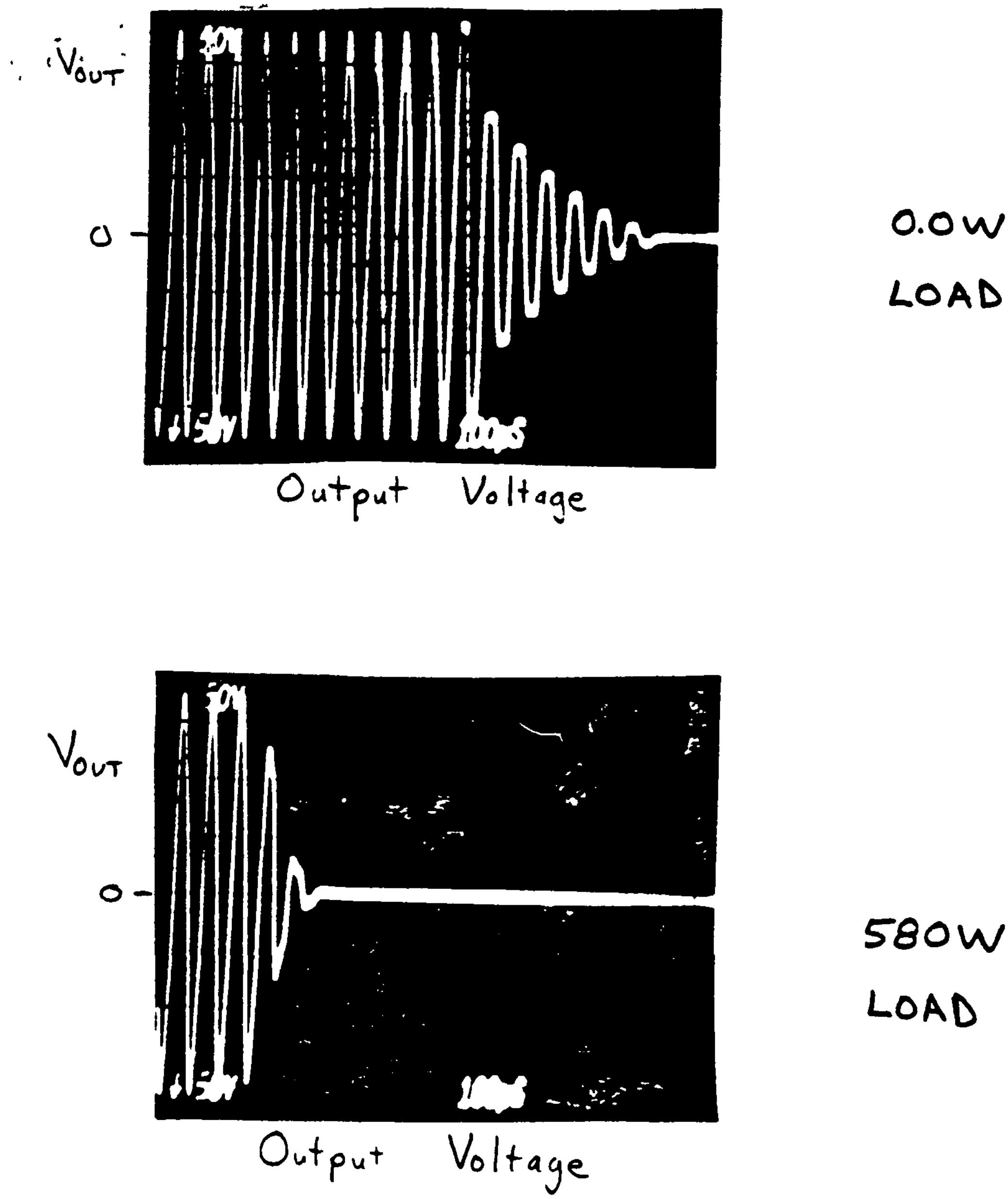


Figure 19. Power Turn Off of a Single Inverter for 0.0 and 580-w Cases

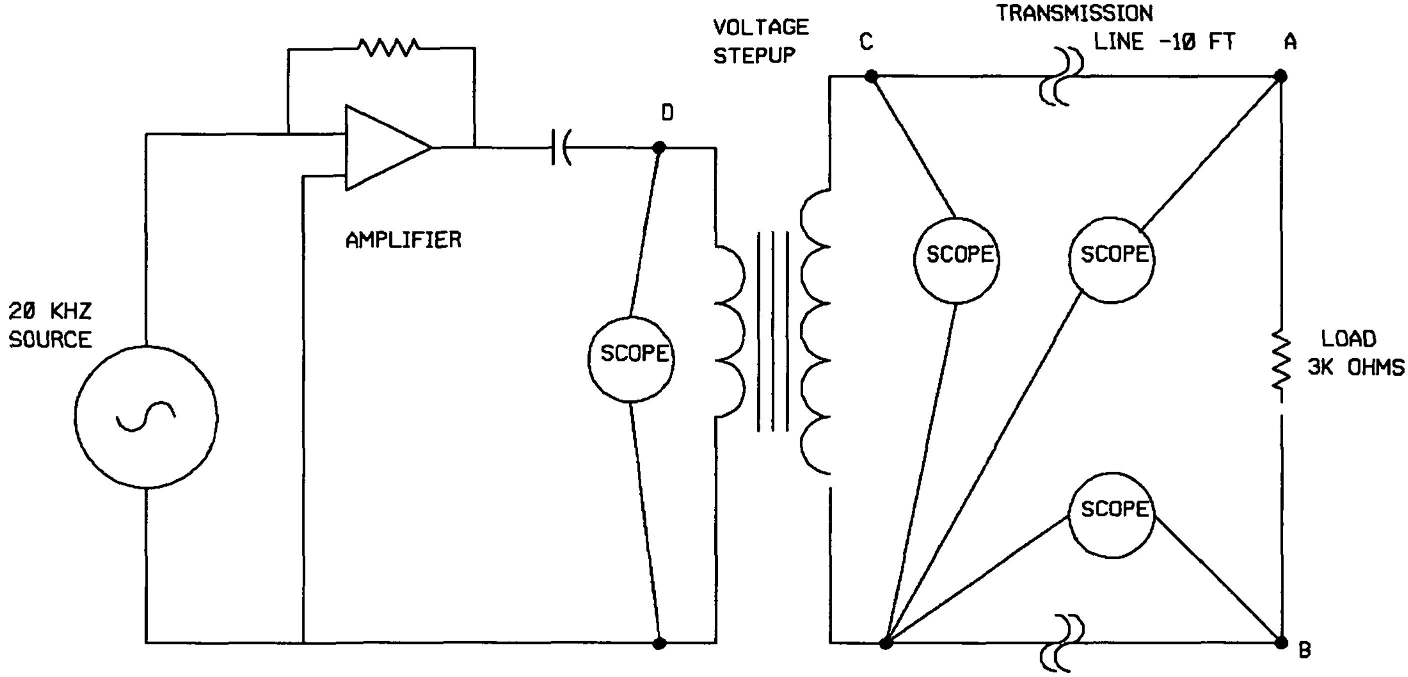


Figure 20. Wire Testing Configuration

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